

# Progress Report on $F_L$ and Diffractive Physics Program to Measure Gluon Distributions in Nuclei

*Thomas Ullrich (BNL)*

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# The Big Questions

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NSAC Long Range Plan '07- Overarching Questions:

*What is the role of gluons and gluon self-interactions in nucleons and nuclei?*

Studying gluons implies measurements of:

1. gluon momentum distributions  $G(x, Q^2)$
2. gluon space time distribution

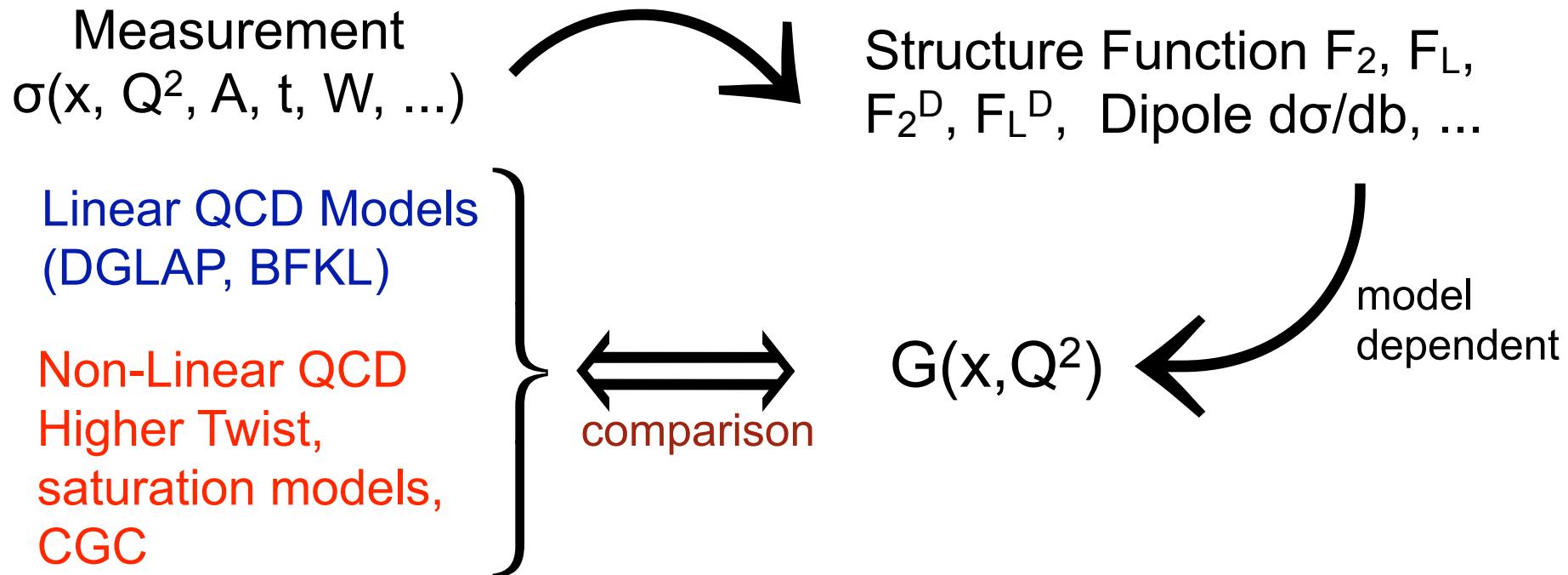
Incremental in ep, transformational in eA

Main Focus (Discovery Potential)

Establishment/Clarification of saturation and validity of CGC approach  $\Rightarrow$  one of the fundamental outstanding problems in QCD

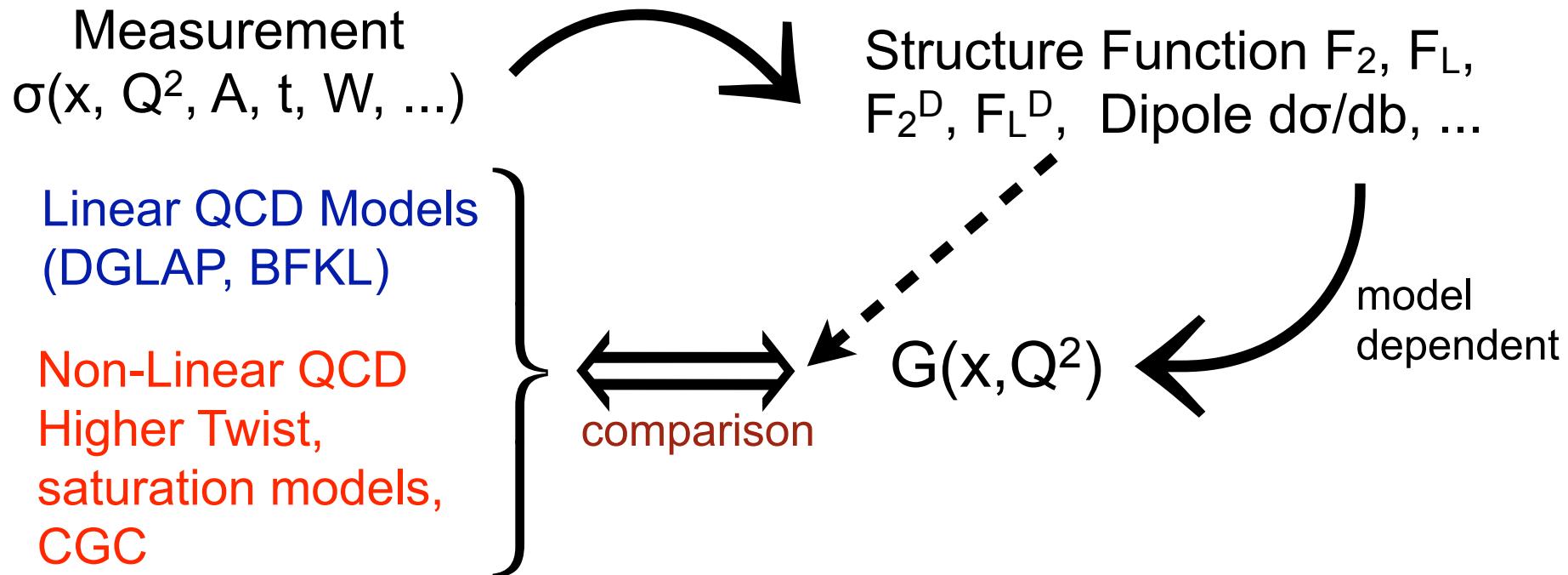
# Gluon Distributions and Saturation

How to probe saturation?  $G(x, Q^2)$  is not an observable!



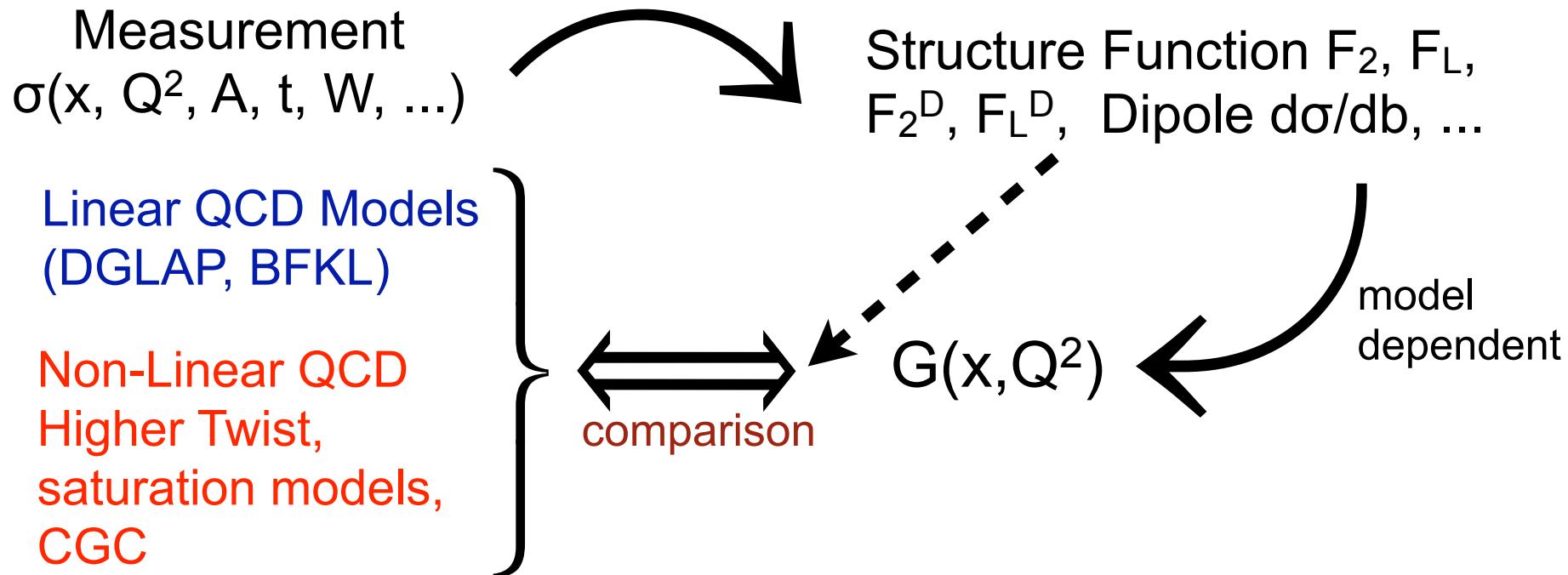
# Gluon Distributions and Saturation

How to probe saturation?  $G(x, Q^2)$  is not an observable!



# Gluon Distributions and Saturation

How to probe saturation?  $G(x, Q^2)$  is not an observable!



Comparison (to constrain/reject models) requires

- ▶ “lever arm” in  $x, Q^2, A, \dots$
- ▶ complementary measurements (incl., semi-incl., excl., DIS & diffractive, varying probes, ...)

# Measurements & Techniques

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- Gluon Distribution  $G(x, Q^2)$ 
  - ▶ Scaling violation in  $F_2$ :  $\delta F_2 / \delta \ln Q^2$
  - ▶  $F_L \sim xG(x, Q^2)$
  - ▶ 2+1 jet rates
  - ▶ Diffractive vector meson production ( $[xG(x, Q^2)]^2$ )
- Space-Time Distribution
  - ▶ Exclusive diffractive VM production ( $J/\psi, \phi, \rho$ )
  - ▶ Deep Virtual Compton Scattering (nGPDs)
  - ▶ Structure functions for various mass numbers A and its impact parameter dependence

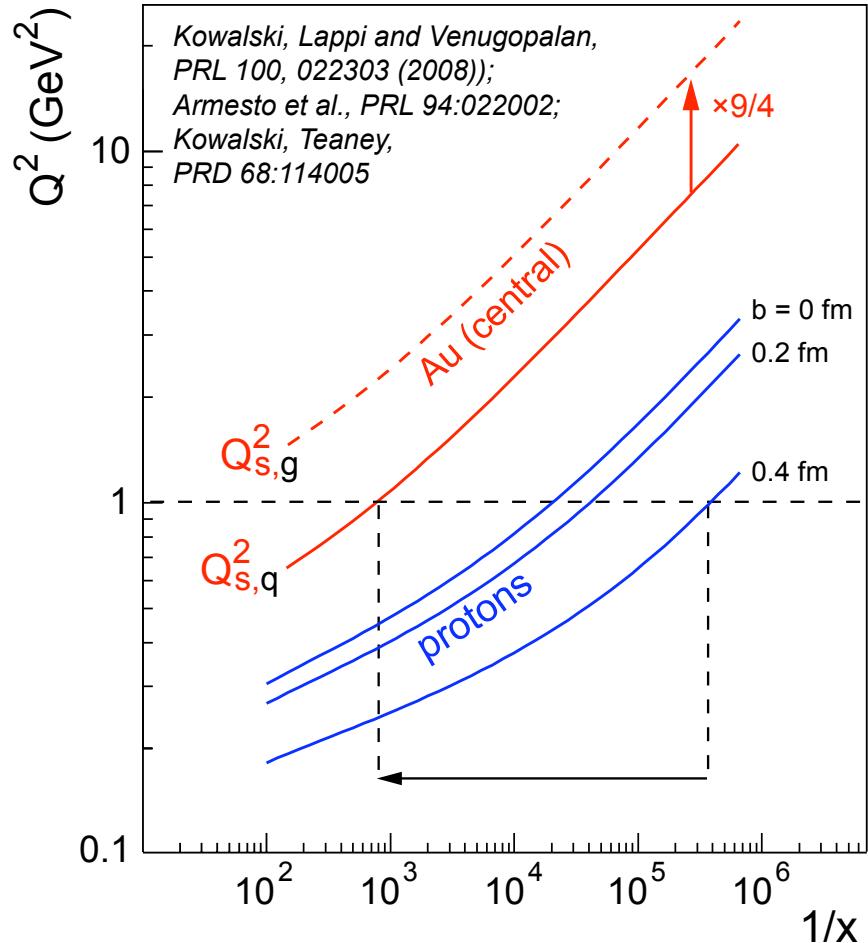


Ongoing studies



On To-Do List

# Saturation & Kinematic Range



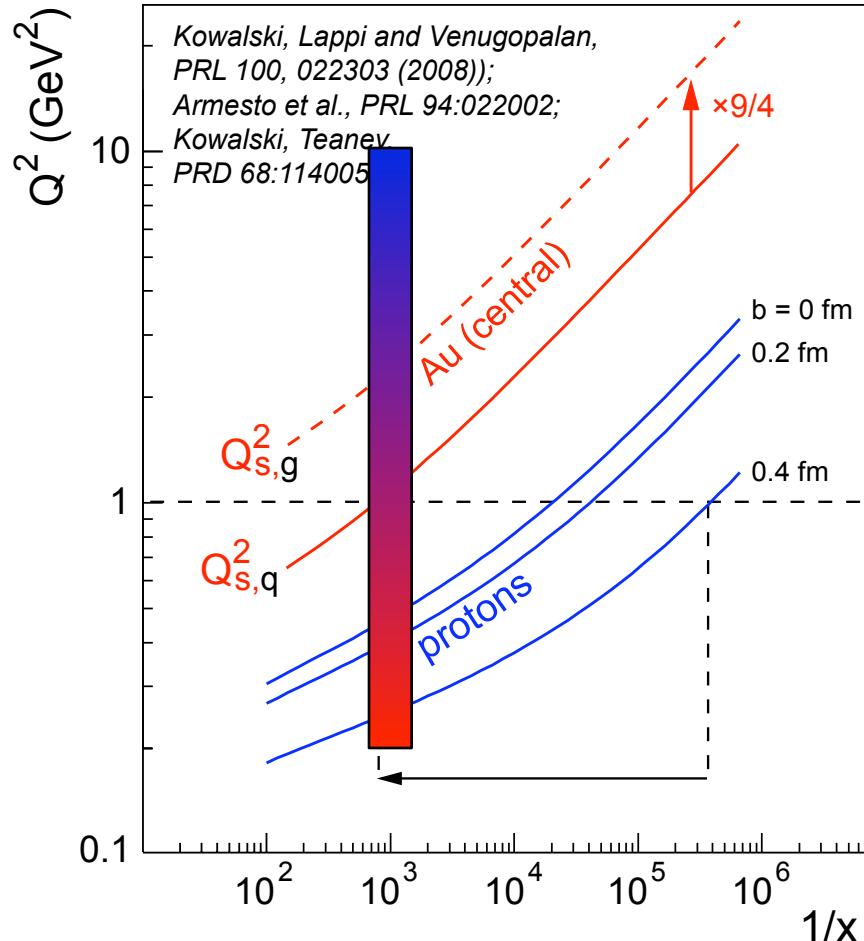
Nuclear Enhancement of  $Q_s$

$$(Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}$$

~6 for Au/U  $\Rightarrow$  at fix  $Q^2$  translates into huge increase in  $x$  (~500)

pp, pA, AA:  $Q_{s,g}$   
DIS (ep, eA):  $Q_{s,q}$

# Saturation & Kinematic Range



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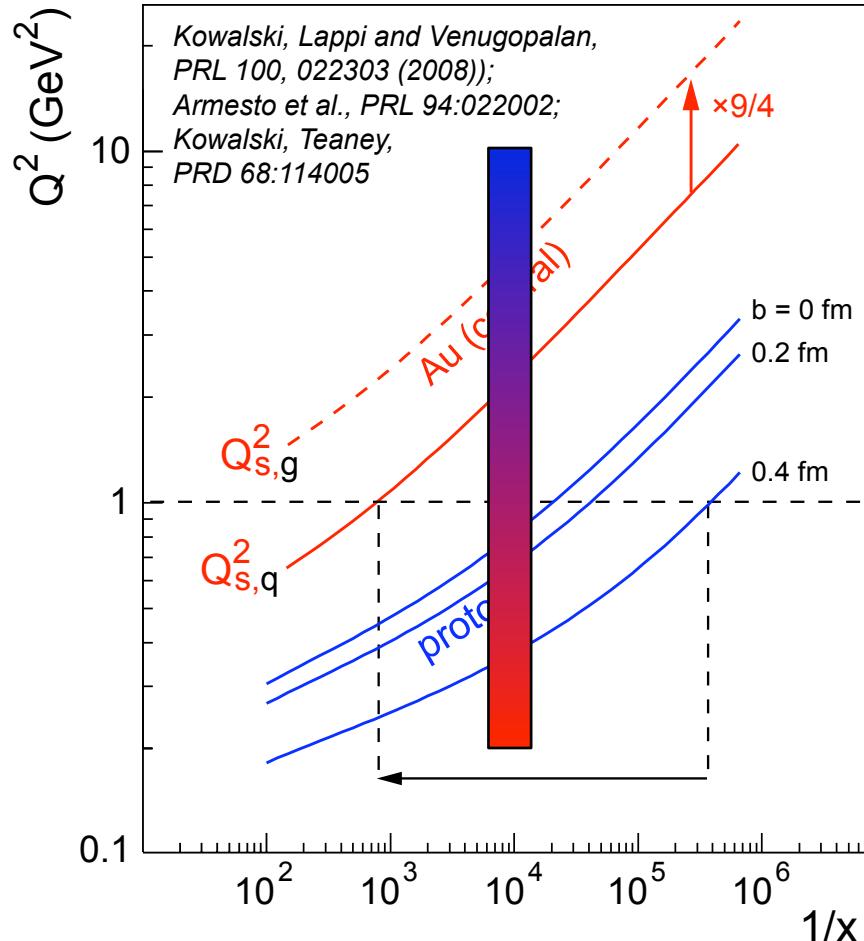
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$x, Q^2$  kinematics:

$x = 10^{-3}$ :  $Q^2 = 0.2 \dots 10$  GeV $^2$   
 $\sqrt{s} = 14 \dots 100$  GeV

# Saturation & Kinematic Range



$E_e + E_A$ (GeV)	$\sqrt{s}$ (GeV)
4+100	40
10+100	63
20+100	89
30+100	110

## Nuclear Enhancement of $Q_s$

$$(Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}$$

~6 for Au/U  $\Rightarrow$  at fix  $Q^2$  translates into huge increase in  $x$  ( $\sim 500$ )

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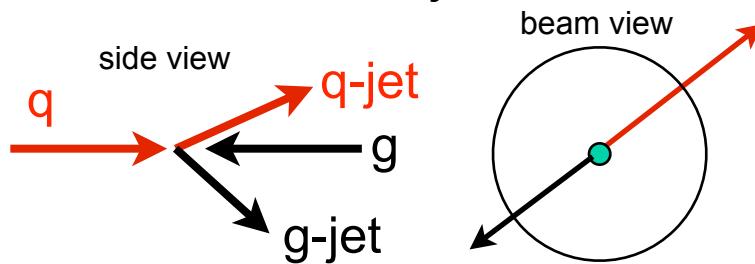
$x = 10^{-3}$ :  $Q^2 = 0.2 \dots 10 \text{ GeV}^2$   
 $\sqrt{s} = 14 \dots 100 \text{ GeV}$

$x = 10^{-4}$ :  $Q^2 = 0.2 \dots 10 \text{ GeV}^2$   
 $\sqrt{s} = 45 \dots 316 \text{ GeV}$

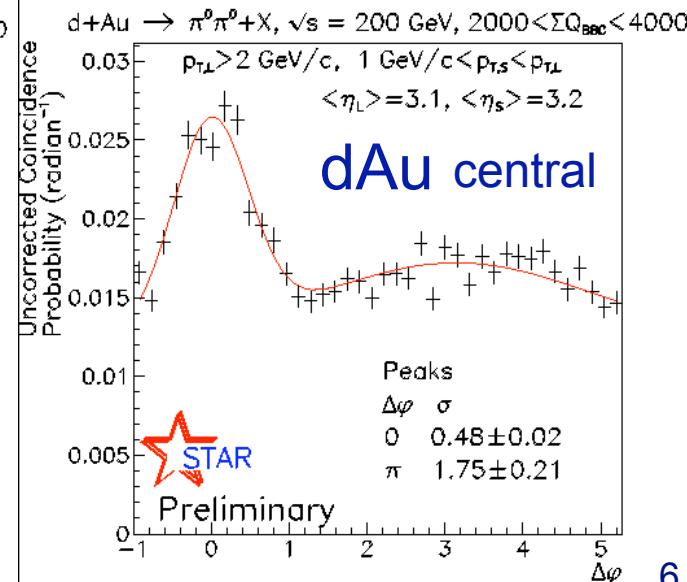
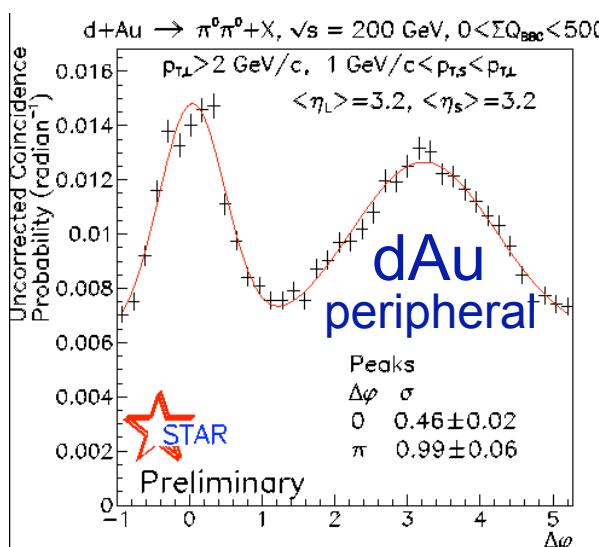
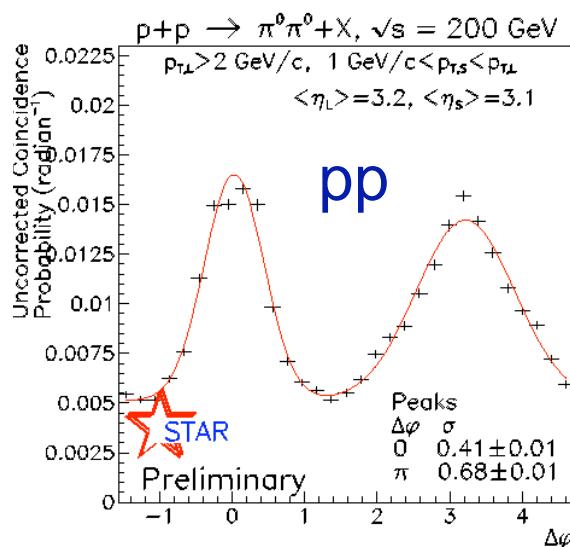
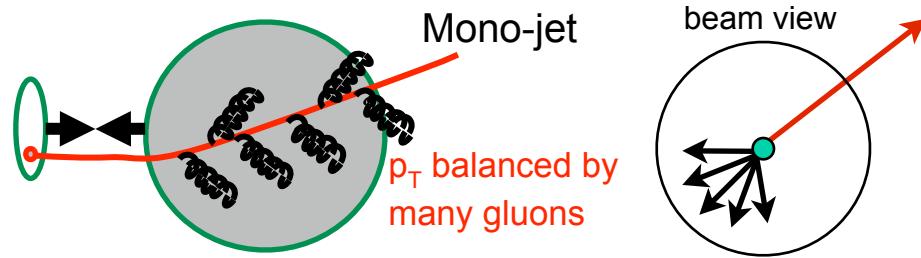
# New Hints from RHIC: Saturation at $x=10^{-3}$ ?

Disappearance of angular correlations in Run 8 dAu data at forward rapidities ( $\log x \sim 2.5 - 3$ )

**Low gluon density (pp):**  
pQCD predicts  $2 \rightarrow 2$  process  
 $\Rightarrow$  back-to-back di-jet



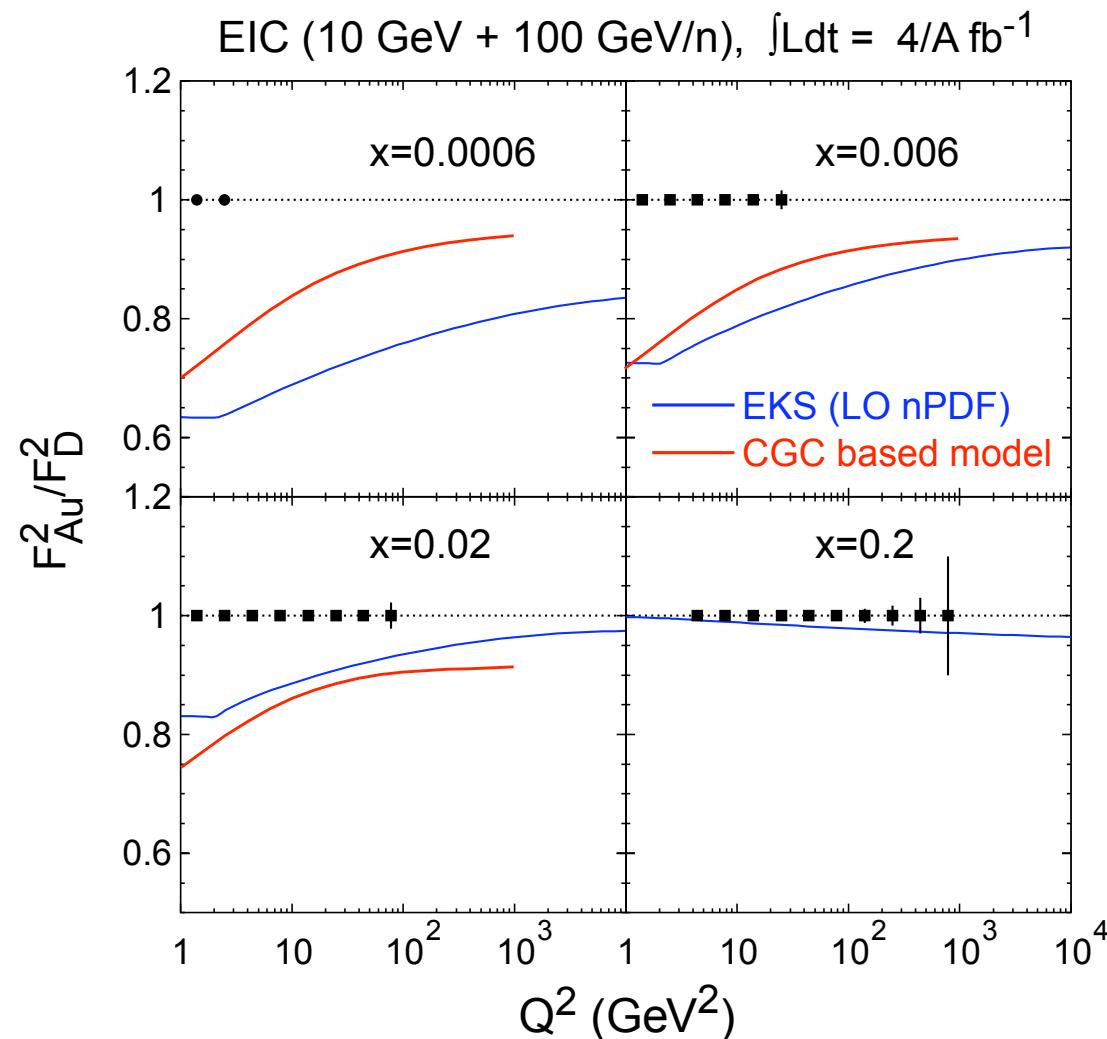
**High gluon density (pA):**  
 $2 \rightarrow 1$  ( $2 \rightarrow \text{many}$ ) process  $\Rightarrow$  mono-jet



# Measuring $F_2$ with the EIC

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$

Inclusive DIS:  
 $F_2$  is day 1 measurement



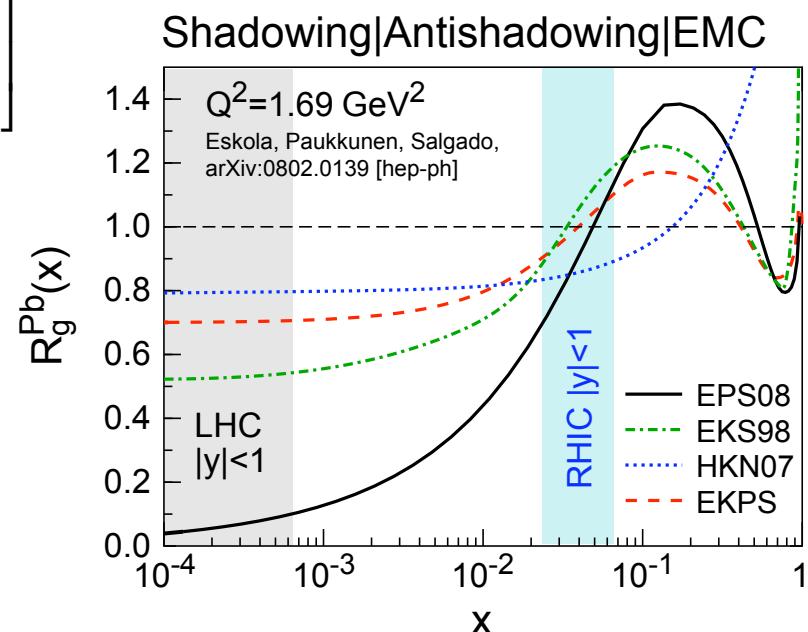
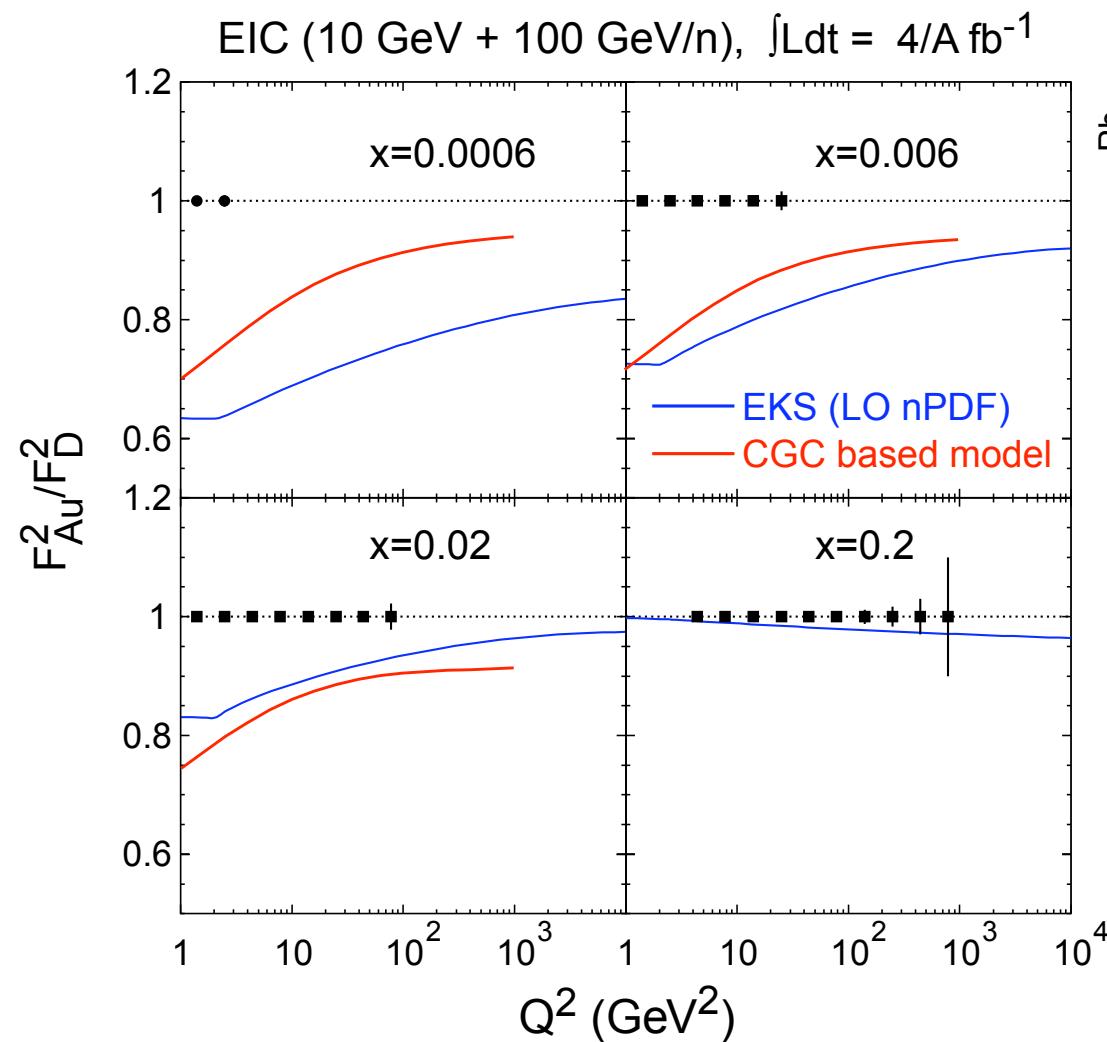
## Assumptions:

- 10 GeV + 100 GeV/n
  - ▶  $\sqrt{s} = 63 \text{ GeV}$
- $Ldt = 4/A \text{ fb}^{-1}$ 
  - ▶ equiv. to  $L = 3.8 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $T = 4 \text{ weeks}$ , duty cycle: 50%
- Detector: 100% efficient
  - ▶  $Q^2$  up to kin. limit  $s \cdot x$
  - ▶ see talk by Elke
- Statistical errors only

Note:  $L \sim 1/A$

# Measuring $F_2$ with the EIC

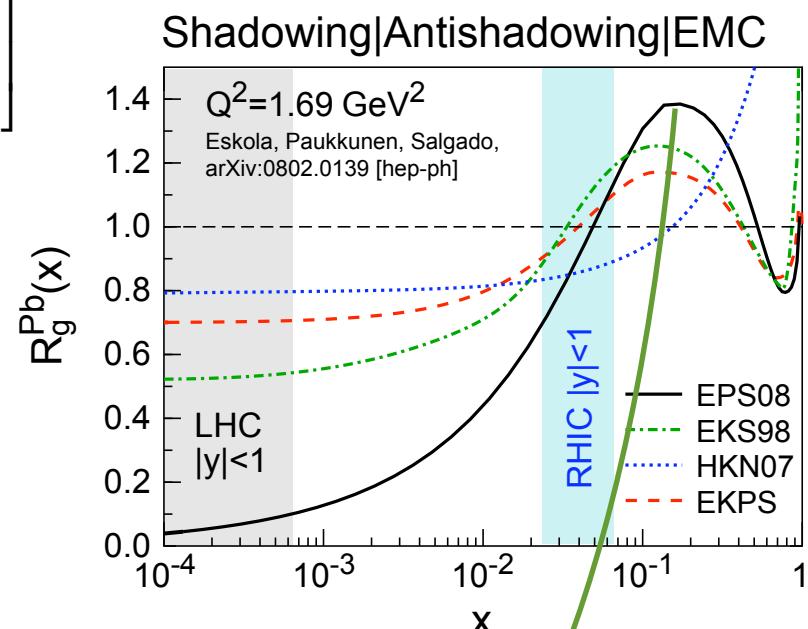
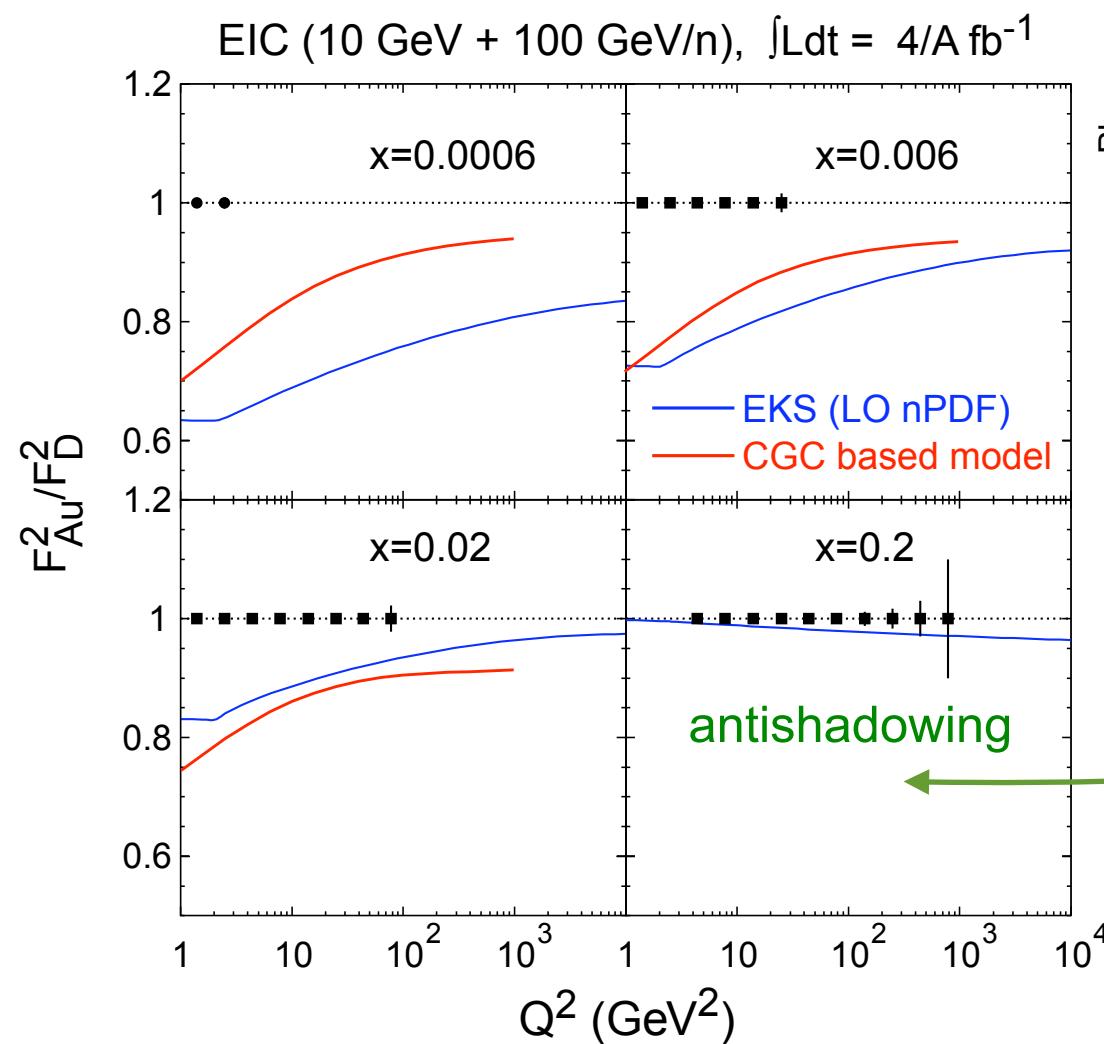
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Initial state effects  
in pA, AA relevant  
for heavy ion program !

# Measuring $F_2$ with the EIC

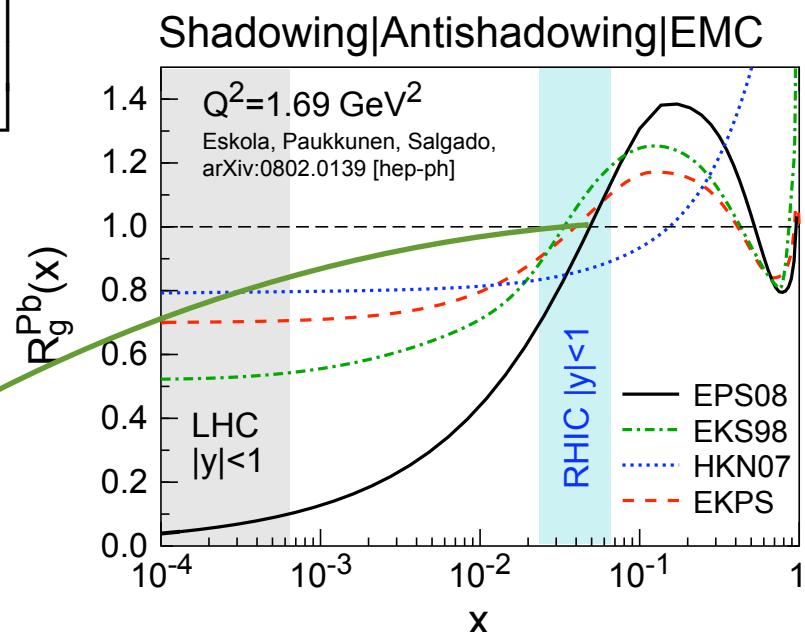
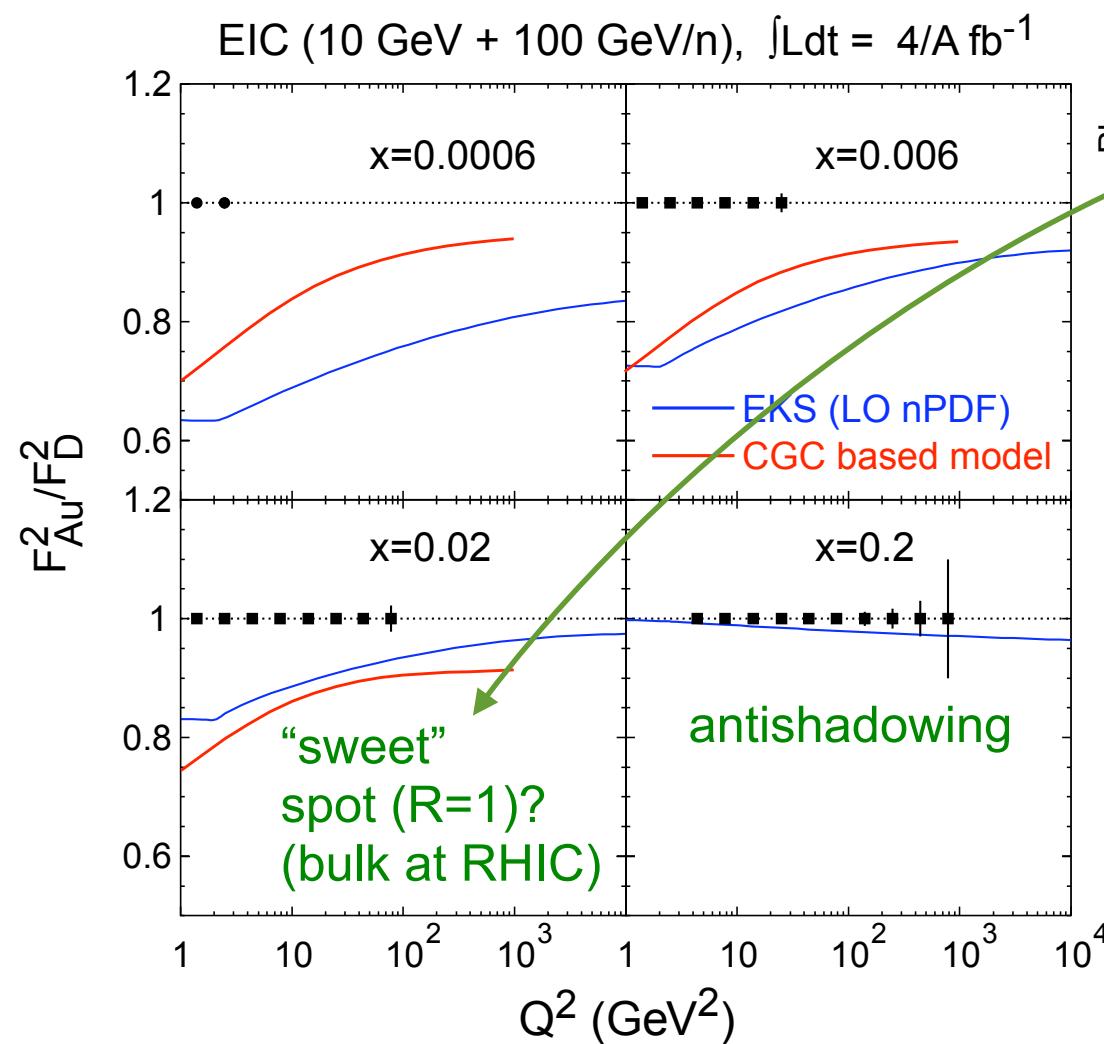
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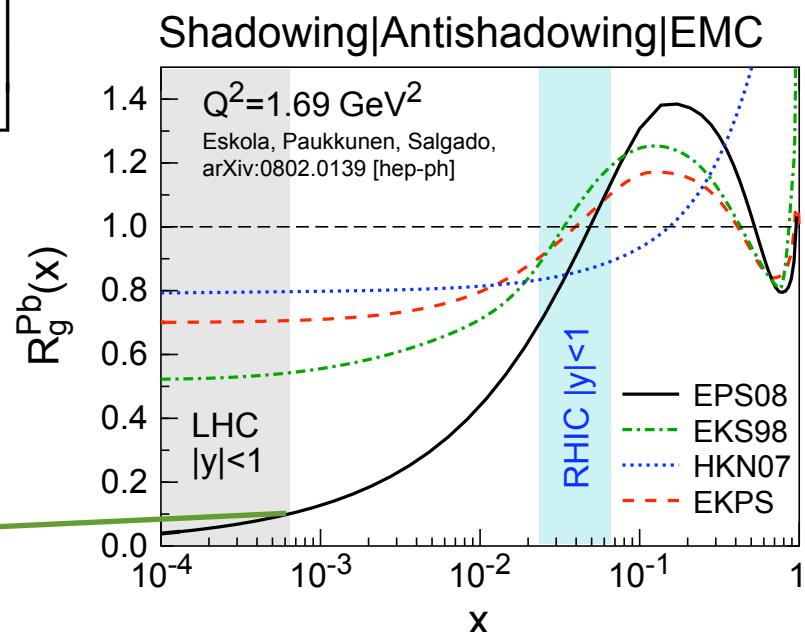
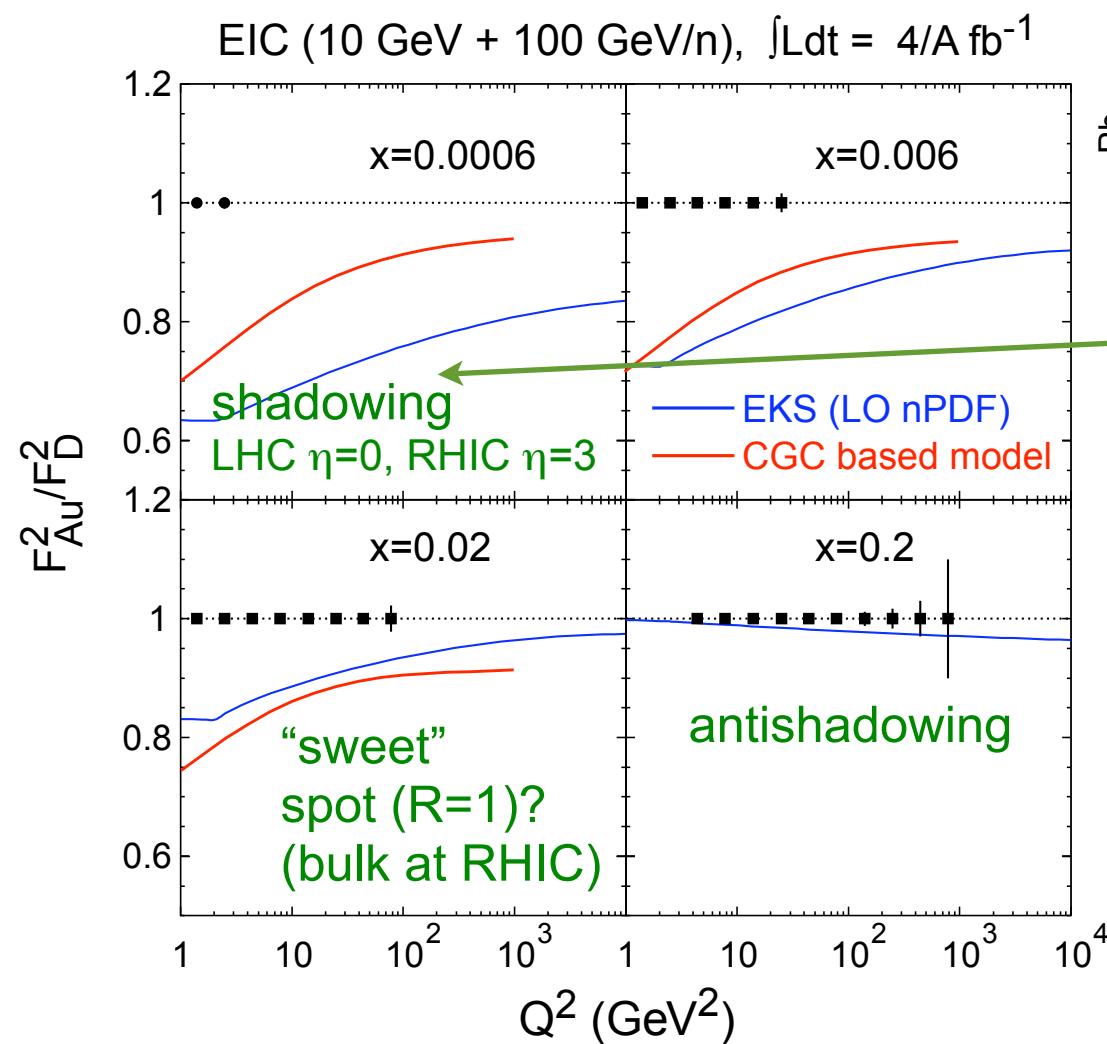
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# Measuring $F_2$ with the EIC

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$



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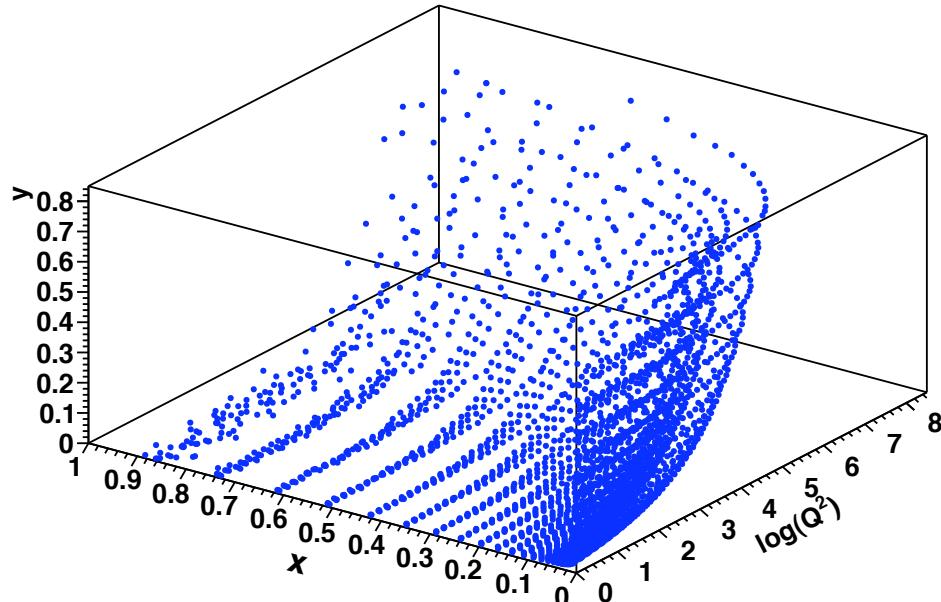
# Measuring $F_L$ with the EIC

$F_L \sim \alpha_s G(x, Q^2)$  : the most “direct” way to  $G(x, Q^2)$

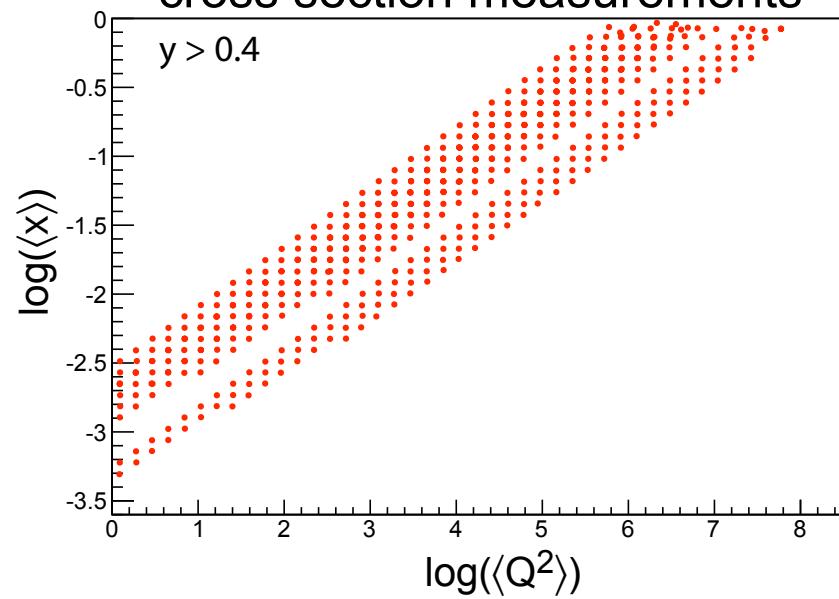
$F_L$  runs at various  $\sqrt{s}$   
⇒ longer program

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$

In order to extract  $F_L$  one needs **at least two measurements** of the inclusive cross section with “wide” span in inelasticity parameter  $y$  ( $Q^2 = sxy$ )



Coverage in  $x$  and  $Q^2$  for inclusive cross section measurements



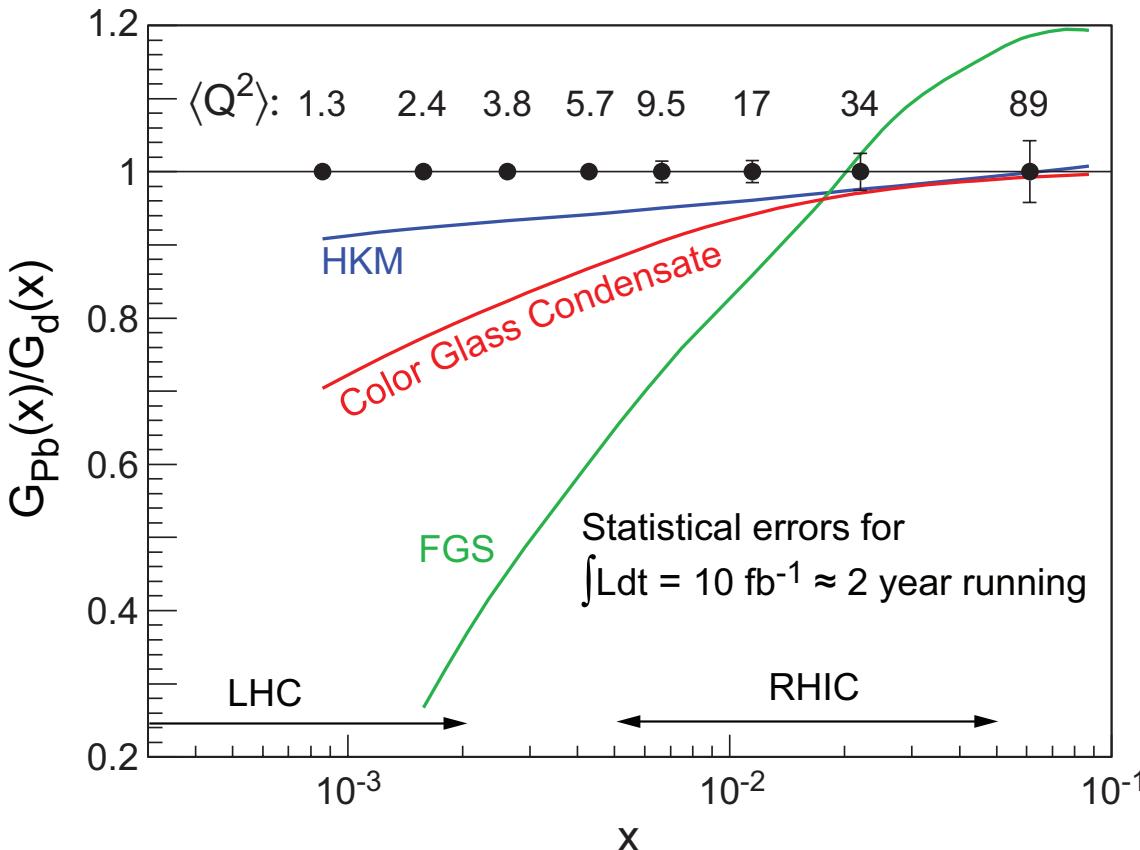
Plots for 4 GeV electrons on 50-250 GeV protons

# Measuring $F_L$ with the EIC

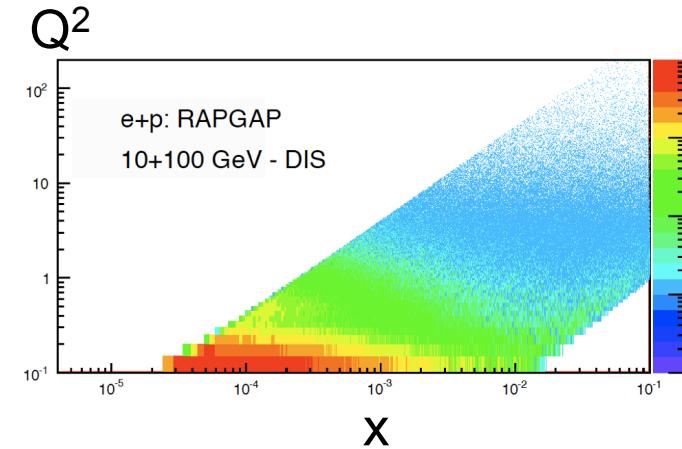
## Assumptions:

- $\int \mathcal{L} dt = 4/A \text{ fb}^{-1}$  (10+100) GeV  
=  $4/A \text{ fb}^{-1}$  (10+50) GeV  
=  $2/A \text{ fb}^{-1}$  (5+50) GeV

- Detector: 100% efficient
  - ▶  $Q^2$  up to kin. limit  $s \cdot x$
- Statistical errors only

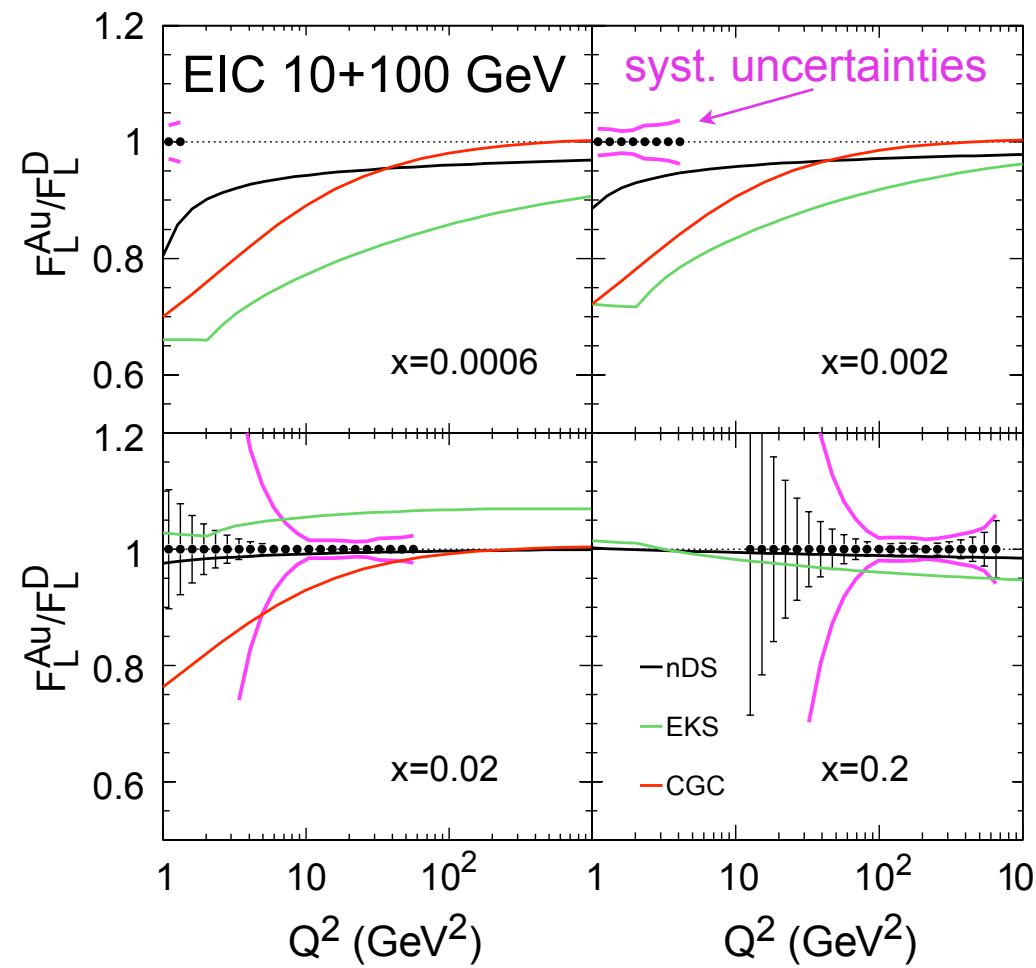


$\langle Q^2 \rangle$  reflects  
kinematic limits



# Measuring $F_L$ : Uncertainties

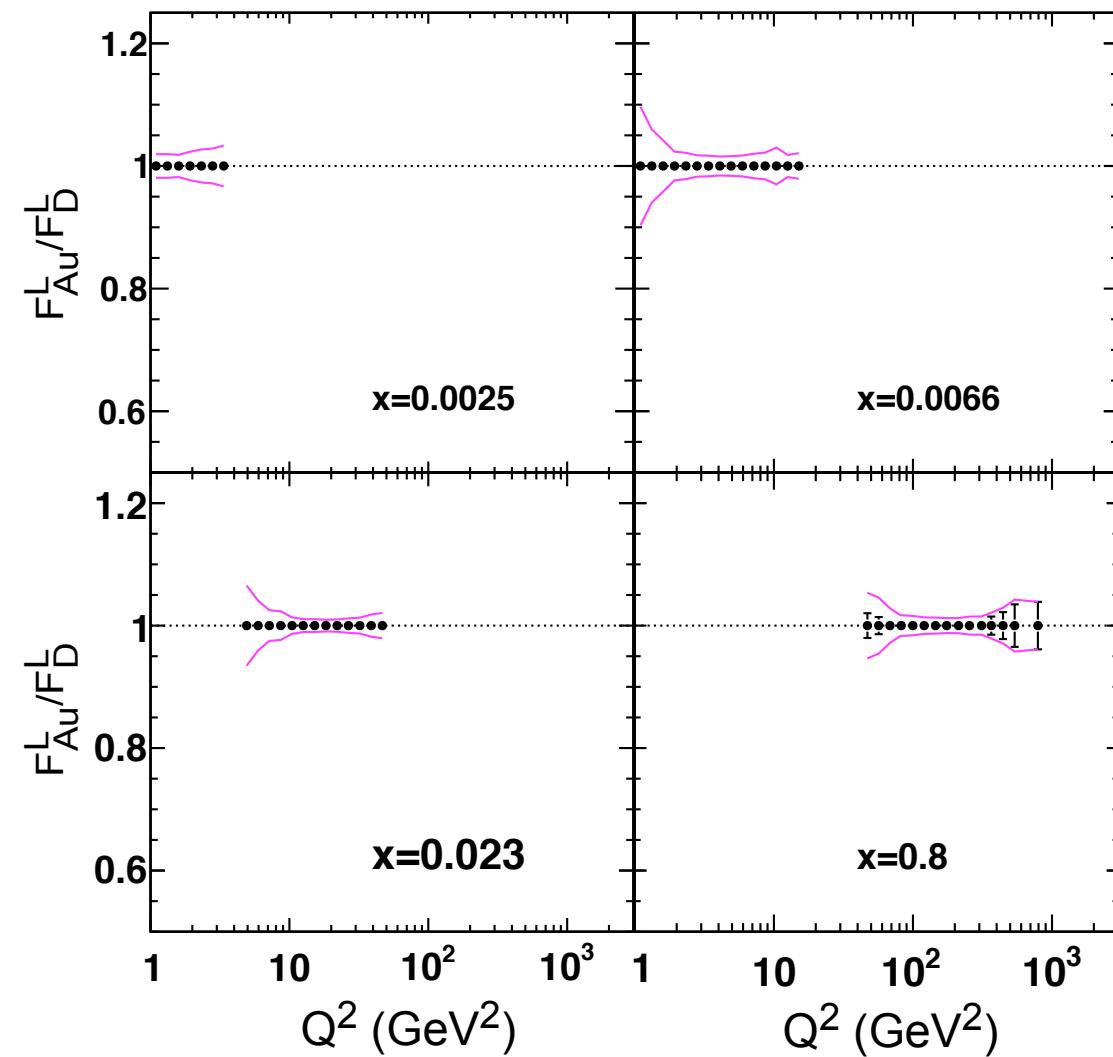
First attempt to get a feeling for systematic uncertainties  
1% energy-to-energy normalization (can we do better?)



- Conclusion from this study:
- Dominated by sys. uncertainties
  - It makes little sense to collect more statistics when dominated by systematical errors
  - Depending on  $x$  and  $Q^2$  might be able take a hit in luminosity  
    ⇒ need more detailed studies (detector simulations)

# $F_L$ for Staged EIC: $E_e = 4$ GeV

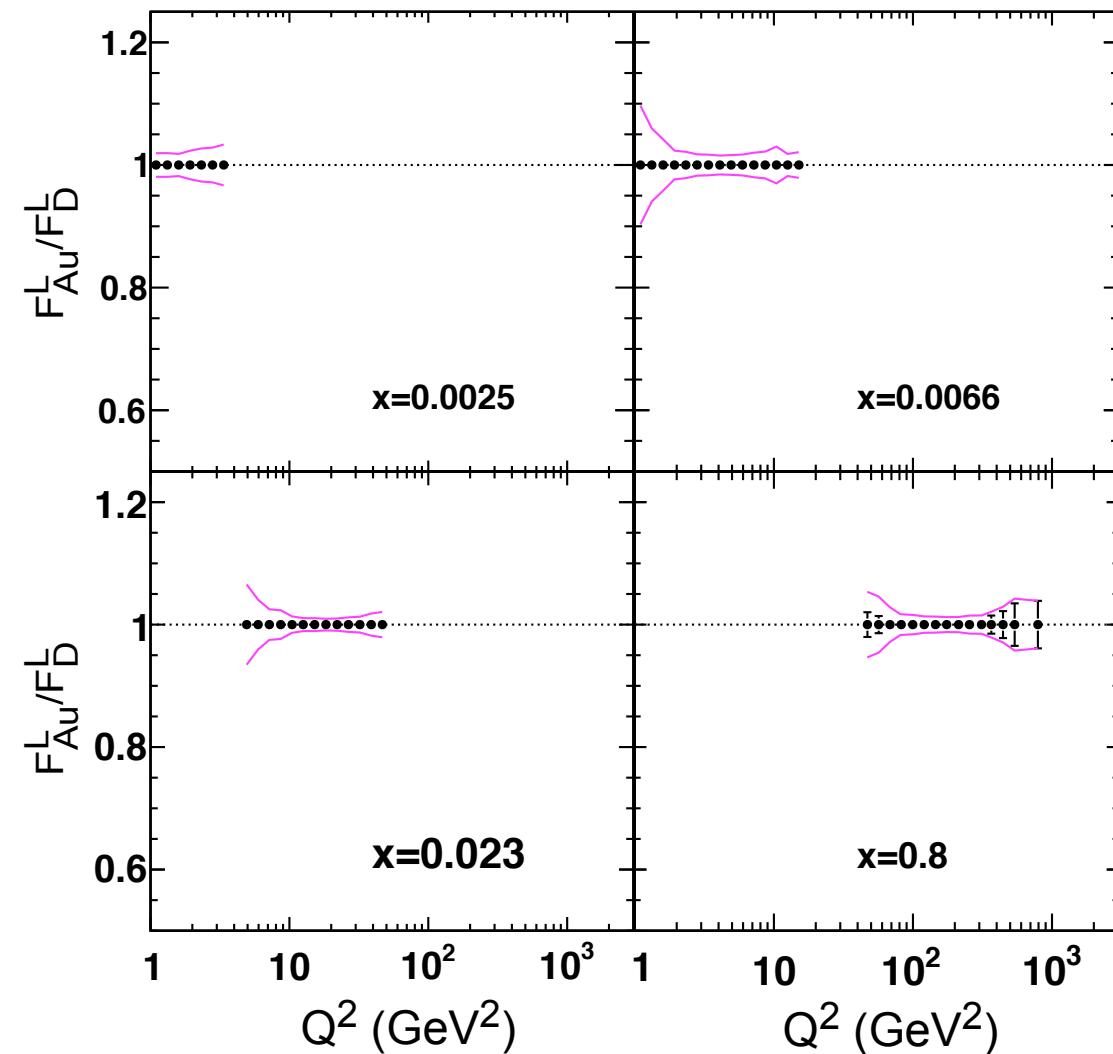
$F_L$  for electron energy fixed at 4 GeV and proton energies:  
50, 70, 100, 250 GeV ( $4\text{fb}^{-1}$  each)



The magenta lines shows the statistical and systematic error (1% uncertainty in normalization) added in quadrature.

# $F_L$ for Staged EIC: $E_e = 4$ GeV

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50, 70, 100, 250 GeV ( $4\text{fb}^{-1}$  each)



The magenta lines show the statistical and systematic error (1% uncertainty in normalization) added in quadrature.

Again, the extraction of  $F_L$  is dominated by systematic uncertainties

# Extracting $G(x, Q^2)$ from Diffractive Events

## General Assumption:

Diffractive processes are the most sensitive means to probe  $G(x, Q^2)$  and saturation since  $\sigma \propto G(x, Q^2)^2$

## Caveats:

- Theoretical
  - ▶ How to extract  $G$  from  $\sigma$  ?
  - ▶ At what scale ( $Q^2$ ) and what  $x$  are we probing  $G$  ?
- Experimental
  - ▶ Detecting diffractive  $eA$  events ?
    - testing breakup of nuclei versus rapidity gap
  - ▶ Separating coherent from incoherent processes
    - How to detect breakup of nuclei ?
  - ▶ How to measure  $t$  ?

*Note: quadratic dependence not for all processes*

# Extracting $G(x, Q^2)$ from Diffractive Events

Smoking Gun (?): exclusive diffractive vector meson production

pQCD: 
$$\frac{d\sigma_L^{\gamma^* A \rightarrow V A}}{dt} \Big|_{t=0} \propto \frac{\alpha_S^2(Q^2)}{Q^6} \boxed{[xG_A(x, Q^2)]^2}$$

Brodsky et al.  
Frankfurt,Koepf,Strikman

but: only valid at large  $Q^2$  ( $Q^2 \gg M_V^2$ )

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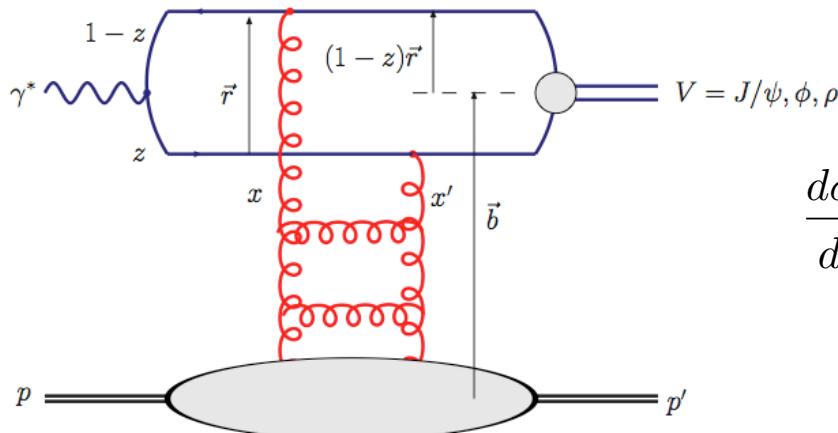
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but: only valid at large  $Q^2$  ( $Q^2 \gg M_V^2$ )

Dipole model:

Kowalski,Motyka,Watt

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow p V}}{dt} = \frac{1}{16\pi} \left| \int dr (2\pi r) \int_0^1 \frac{dz}{4\pi} \int db (2\pi b) (\Psi_V^* \Psi)_{T,L} J_0(b\Delta) J_0([1-z]r\Delta) \frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} \right|^2$$



$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{b}} = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b) \right) \right]$$

Glauber-Mueller

# Modeling Diffractive VM Production

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Implemented various dipole models (b-Sat, b-CGC) in a single program (xdvmp) for ep and recently for eA.

Various VM wave functions are implemented. The implementation of the pQCD model is underway.

(Dipole: H. Kowalski, L. Motyka, G. Watt, PhysRev D74, 074016, arXiv:hep-ph/0606272v2; Henri Kowalski , Derek Teaney, PRD68:114005, hep-ph/0304189; H. Kowalski, T. Lappi, R. Venugopalan, PRL100:022303, arXiv:0705.3047 [hep-ph]

pQCD: S. Brodsky et al., Phys.Rev.D50:3134,1994, e-Print: hep-ph/9402283; L. Frankfurt et al., Phys. Rev. D 54, 3194 - 3215 (1996); L. Frankfurt et al., Phys.Rev.D57:512,1998, hep-ph/9702216)

The dipole model describes VM ( $J/\psi$ ,  $\phi$ ,  $\rho$ ) production at HERA very well.

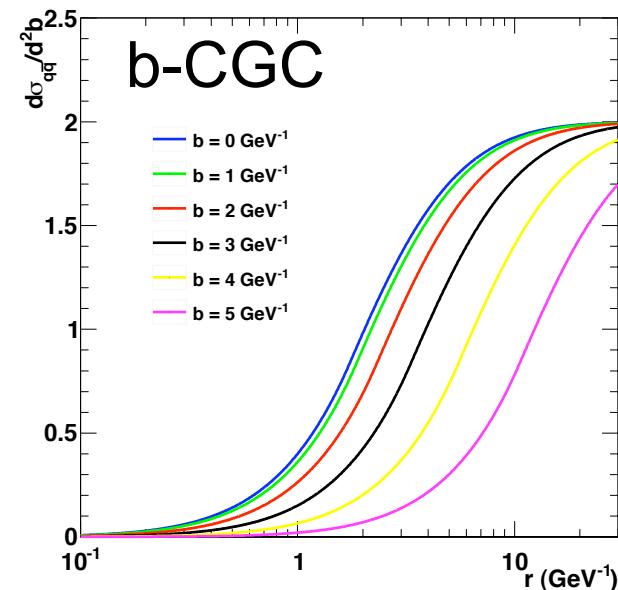
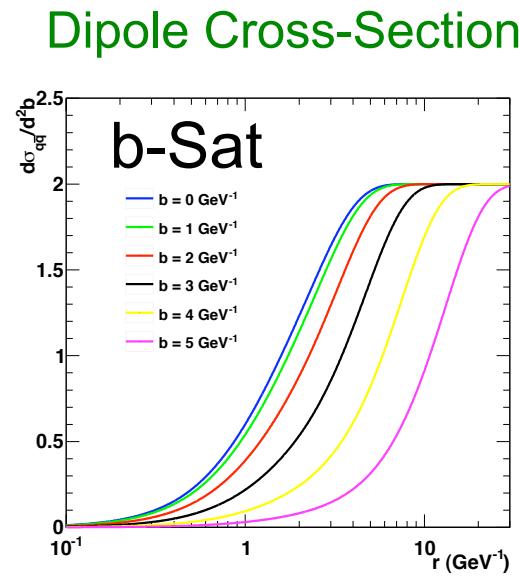
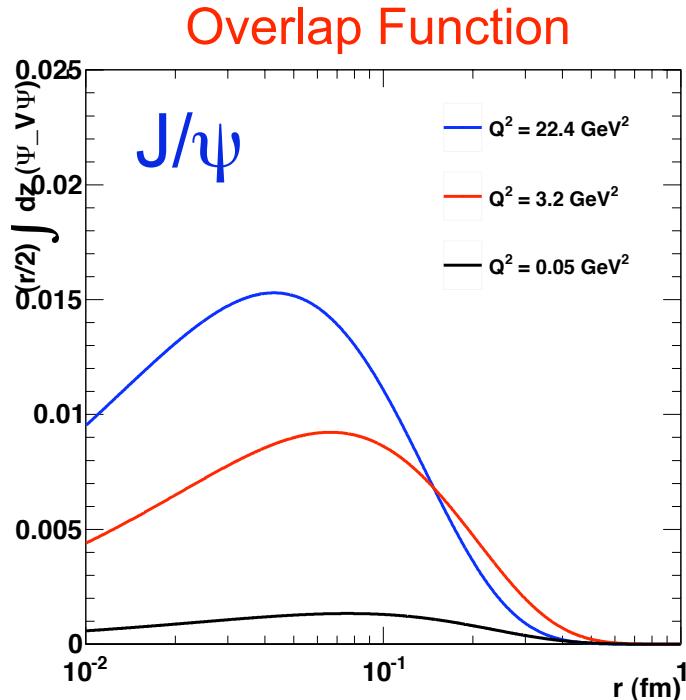
Both will be used to test sensitivity to different  $G(x, Q^2)$  and can be used in detector simulations.

# First Lessons Learned for EIC

Cross-section for production of final state VM:

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow Ep}}{dt} = \frac{1}{16\pi} |\mathcal{A}_{T,L}^{\gamma^* p \rightarrow Ep}|^2 = \frac{1}{16\pi} \left| \int d^2 r \int_0^1 \frac{dz}{4\pi} \int d^2 b (\Psi_E^* \Psi)_{T,L} e^{-i[\mathbf{b} - (1-z)\mathbf{r}] \cdot \Delta} \frac{d\sigma_{q\bar{q}}}{d^2 b} \right|^2$$

Amplitude                      Overlap between photon and VM wave function              Dipole Cross-Section

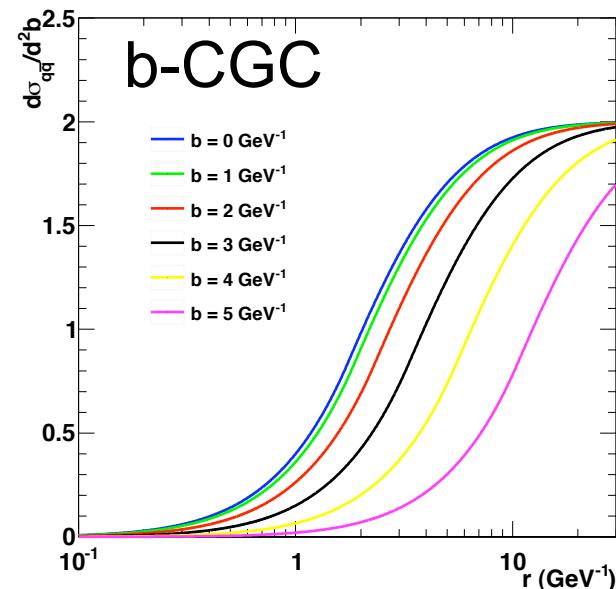
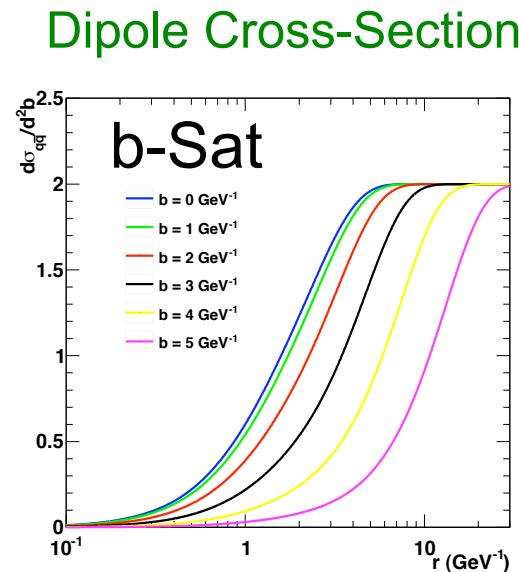
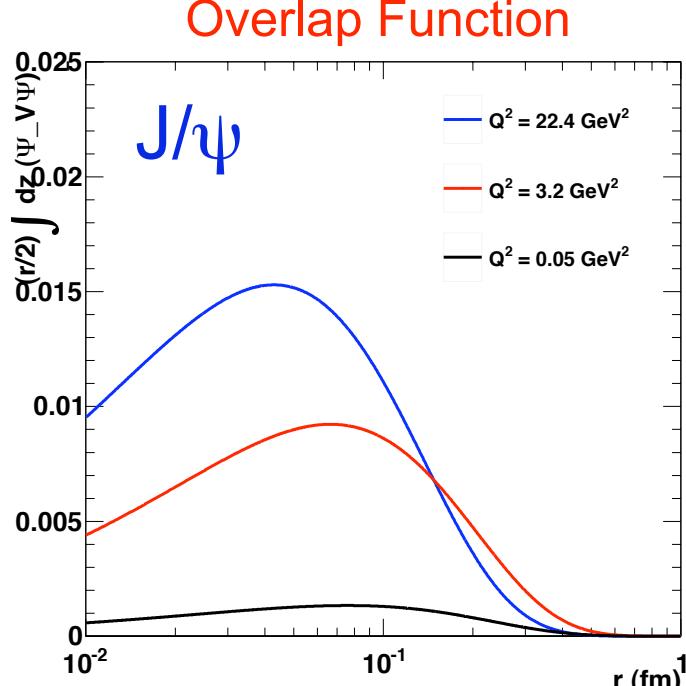


# First Lessons Learned for EIC

Cross-section for production of final state VM:

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Amplitude                                      Overlap between photon and VM wave function                      Dipole Cross-Section



$$\frac{d\sigma_{q\bar{q}}}{d^2 b} = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b) \right) \right].$$

# First Lessons Learned for EIC

Cross

$$\frac{d\sigma_{T,l}^{\gamma^* l}}{d}$$

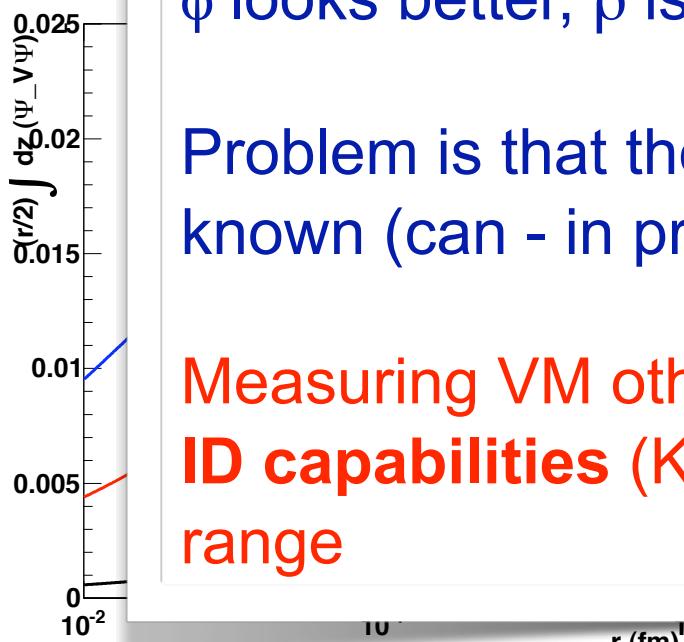
Overlap function vanishes for large dipole radii where saturation kicks in ( $Q \sim 1/r$ )

The  $J/\psi$  seems too small to probe saturation physics

$\phi$  looks better,  $\rho$  is ideal

Problem is that the wave functions for  $\rho$ ,  $\phi$  are less known (can - in principle - be solved)

Measuring VM other than  $J/\psi \rightarrow \ell^+\ell^-$  requires **particle ID capabilities** ( $K, \pi$ ) of the detector over a wide  $p_T$  range

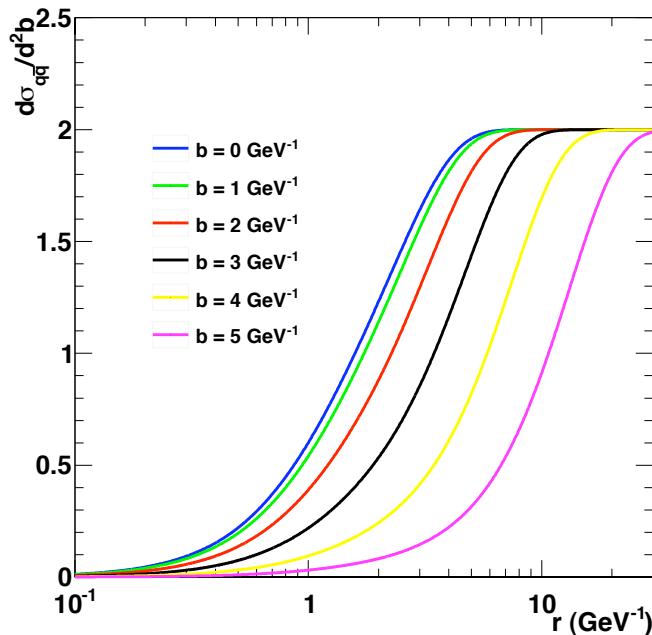


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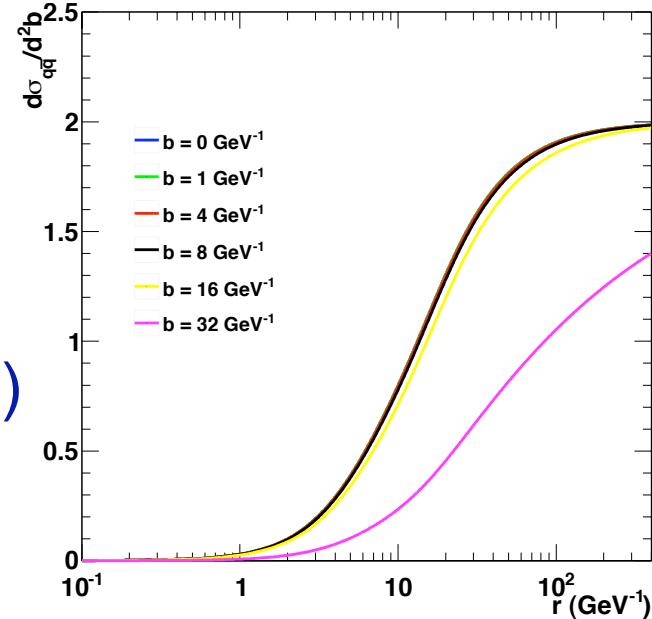
# From ep to eA ...

(All xdvmp)

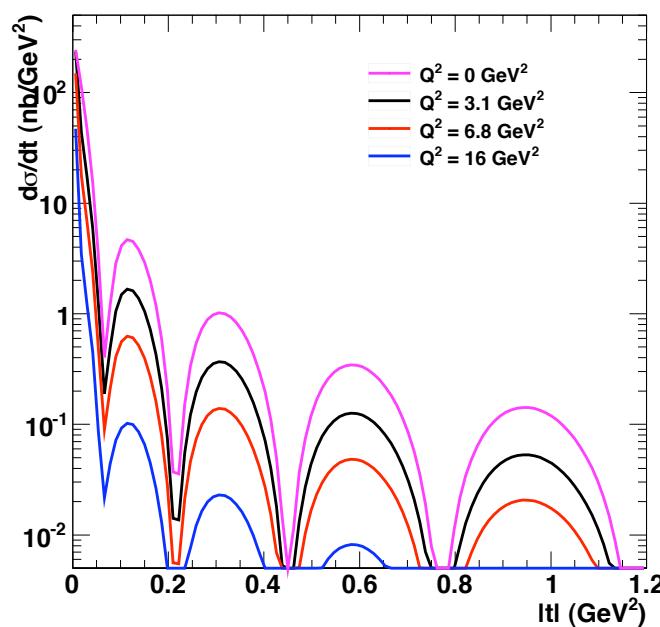
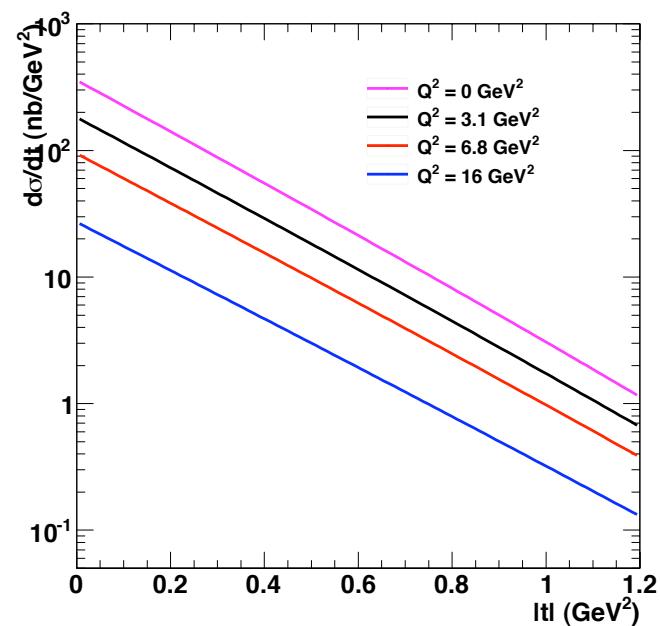
ep →



eA →

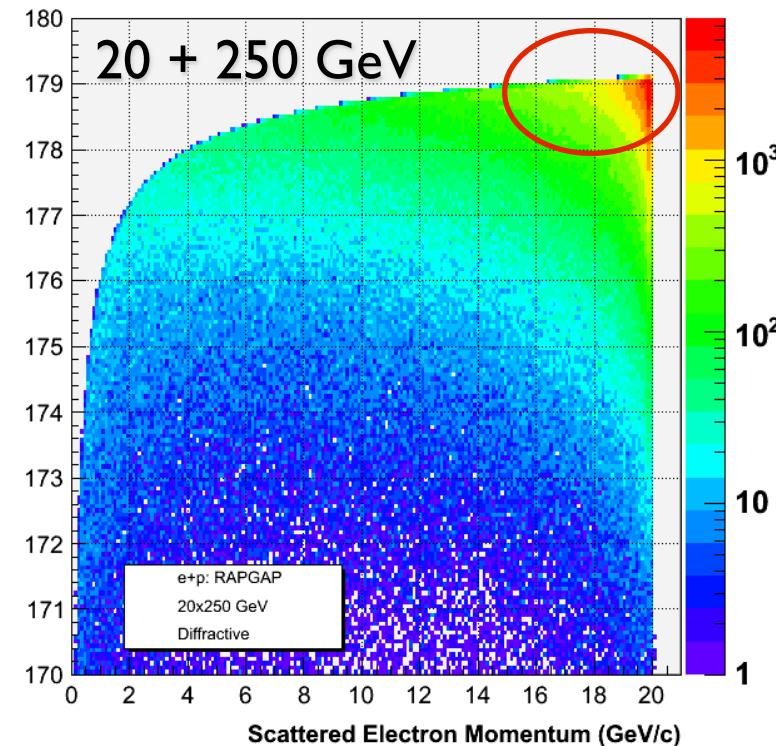
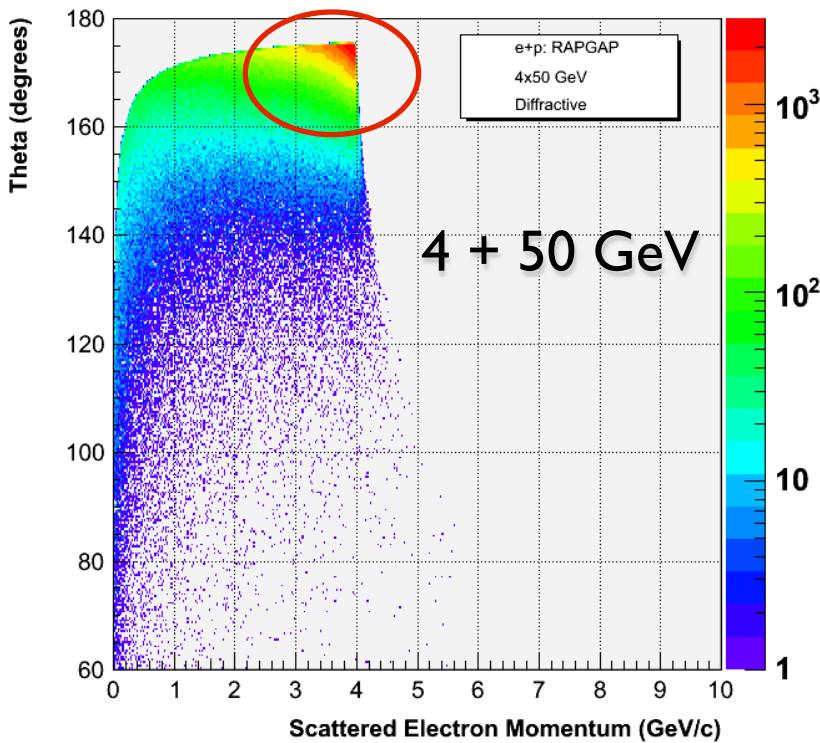


Note: eA is less  
b dependent than  
ep (which is good)



# Diffractive Physics is Experimentally Hard

## Scattered Electron $\theta(p)$



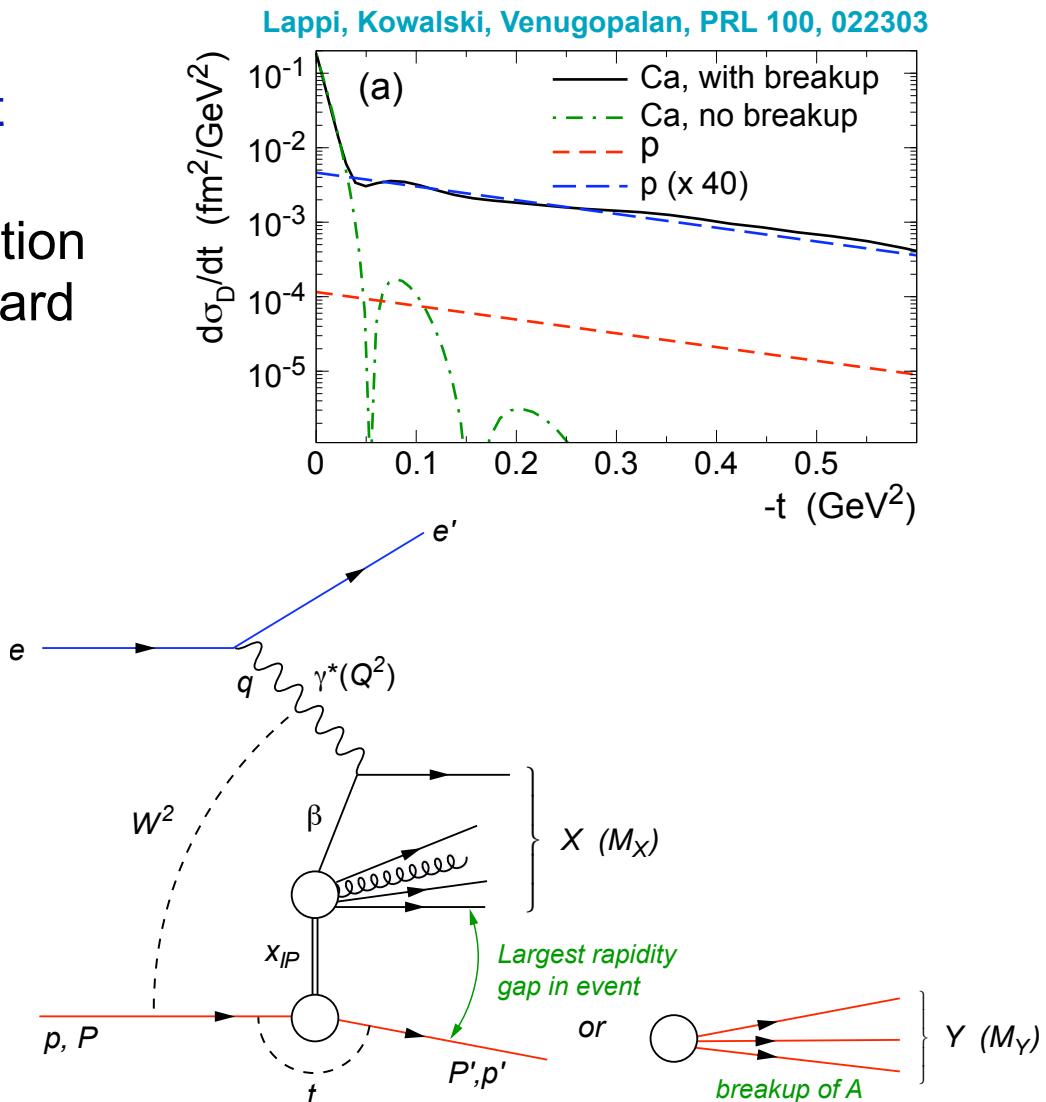
Stringent constraints on detector:

Need to measure electrons (PID + p) down to very low angles (up to  $1^\circ$  off the beam line)  
⇒ need dipole magnet(s) to bend e in “sane” region

# Identifying Diffractive Events

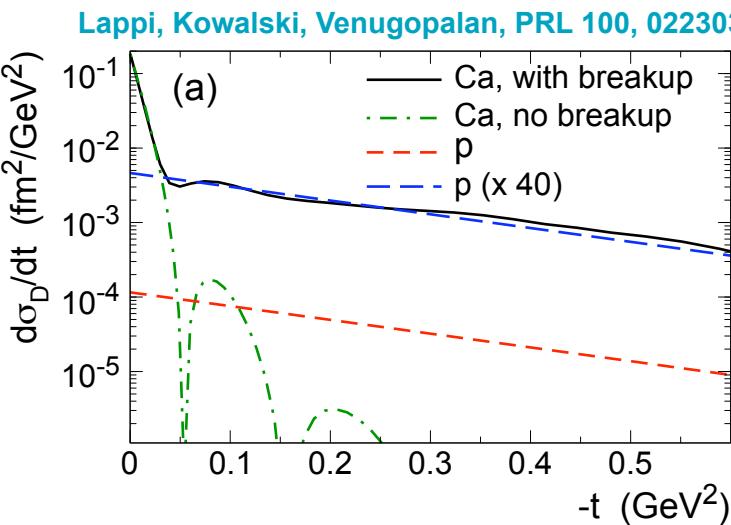
- Beam angular divergence limits smallest outgoing  $p(A)$  angle that can be measured
- Cannot measure coherent diffraction in heavy ions (small  $t$ ) using forward spectrometry (Roman Pots)
  - separate ion only if  $p_T > p_{T,\min}$
  - possible for  $p$  and light ions
- Can determine  $t$  in exclusive production from  $e, e', X$

species (A)	$p_T^{\min}$ (GeV/c)
d (2)	0.02
Si (28)	0.22
Cu (64)	0.51
In (115)	0.92
Au (197)	1.58
U (238)	1.90



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- Need to rely on rapidity gap method
  - ▶ simulations look good
  - ▶ high efficiency, high purity possible with gap *alone*
    - ~1% contamination,
    - ~80% efficiency
  - ▶ depends critically on hermeticity of detector
  - ▶ improve further by veto on breakup of nuclei (DIS)
- Very critical:
  - ▶ Mandatory to detect nuclear fragments from breakup
  - ▶ n: Zero-Degree Calorimeter
  - ▶ p, A<sub>frag</sub>: Forward Spectrometer
  - ▶ New idea: Use U instead of Au (fission)

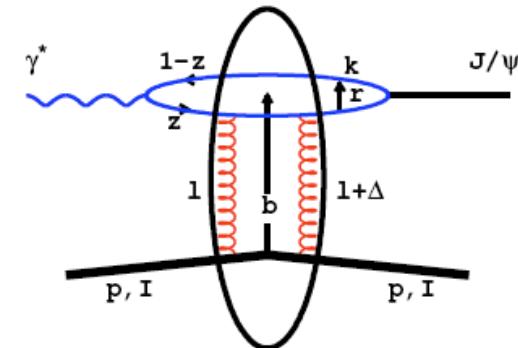
# New: Probing Gluonic Structure of Nuclei

Basic Idea: Studying diffractive exclusive  $J/\psi$  production at  $Q^2=0$  (photo-production)

(H. Kowalski & A. Caldwell)

## Ideal probe

- large photo-production cross sections
- $t$  can be derived from  $e$ ,  $e'$ , and  $J/\psi$  4-momentum
  - ▶ no measurement of ion momentum necessary
  - ▶ beam electron  $p_T < 1$  MeV (0.2 with cooling MeV) for  $E < 5$  GeV
  - ▶ scattered electron can be detected in the forward detector (beam optic needs to be studied)
- small width well separated from background
- $J/\psi$  dipole interacts only by 2g exchange at low  $x$ 
  - ▶ process is well understood in QCD



# Probing Gluonic Structure of Nuclear Forces

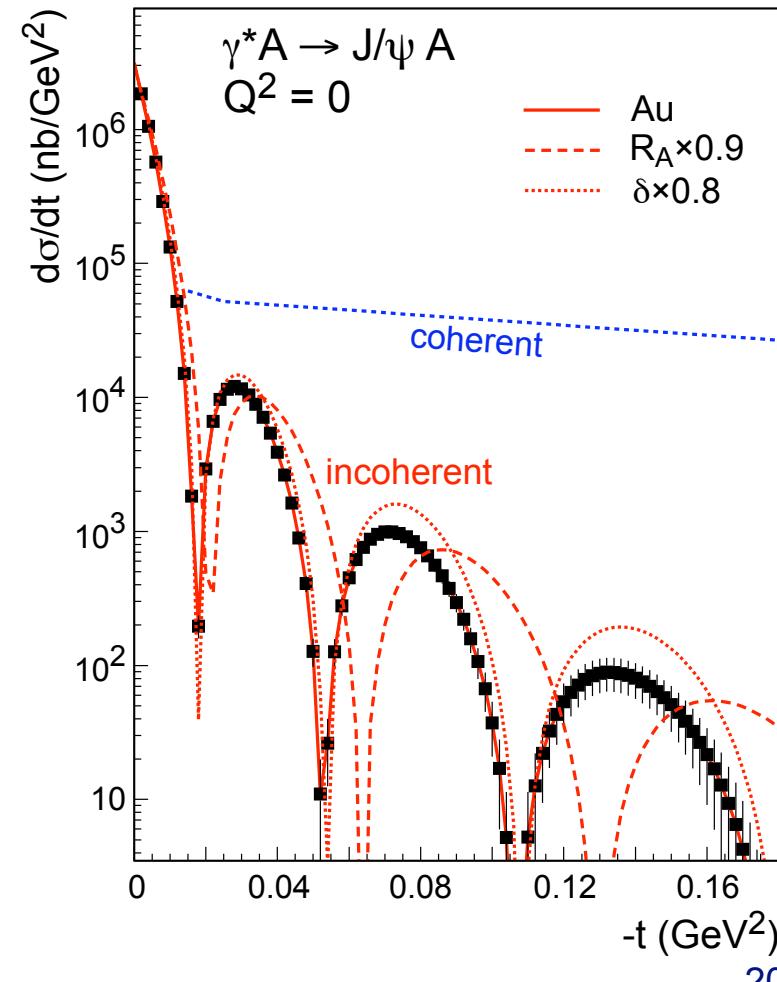
Simplified assumption for proof of principle:

- Random and uncorrelated distribution of nucleons within the nucleus
- Shape of the nucleus given by the Woods-Saxon distribution  $\rho(b_T)$
- Average (sum) over all configurations
- Fourier transform the average  $\Rightarrow d\sigma_A/dt$

Promising method to measure  
gluon form factor  $F_g$  in nuclei

Crucial:

- Need to suppress background by factor 100
- Dynamics of nuclear disintegration?
  - ▶ studies underway (QMD?)
  - ▶ easier with Uranium?



# Summary

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## Study of measurements of $G(x,Q^2)$ in progress

- $F_2$  (existing studies but not updated yet)
- $F_L$  (EIC & staged EIC)
- 2+1 jets (EIC & staged EIC) [not shown, see add, material]
- Diffractive VM production - no error evaluation yet but all we need is there

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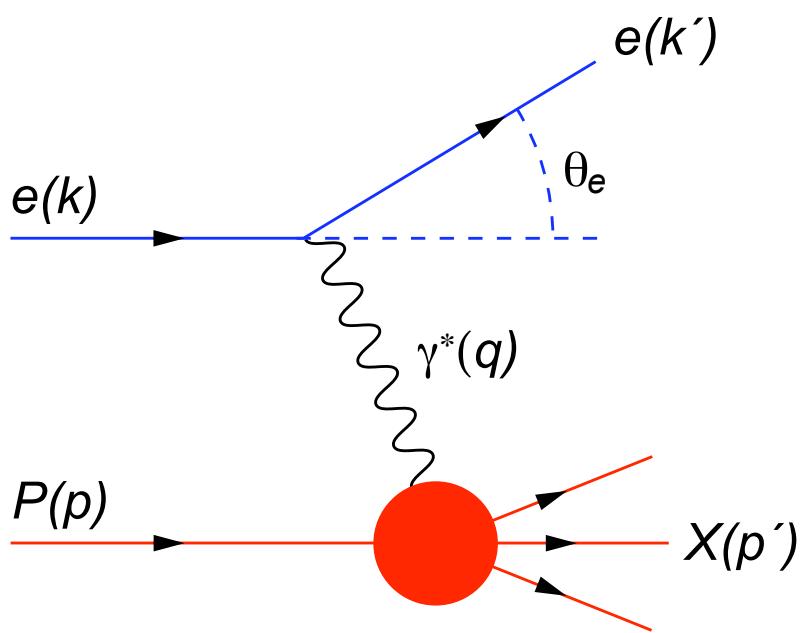
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## Next Steps

- Further investigate nuclear breakup
- Simulation on diffractive VM
- Run measurements through detector simulation (see Elke's talk)

# Additional Slides

# Deep Inelastic Scattering (DIS)



Resolution power (“Virtuality”):

$$Q^2 = -q^2 = -(k - k')^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Inelasticity:

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2\left(\frac{\theta'_e}{2}\right)$$

p fraction of struck quark

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

$$\frac{d^2\sigma^{ep \rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$$

quark+anti-quark  
momentum distributions

gluon momentum  
distribution

# Hard Diffraction in DIS at Small $x$

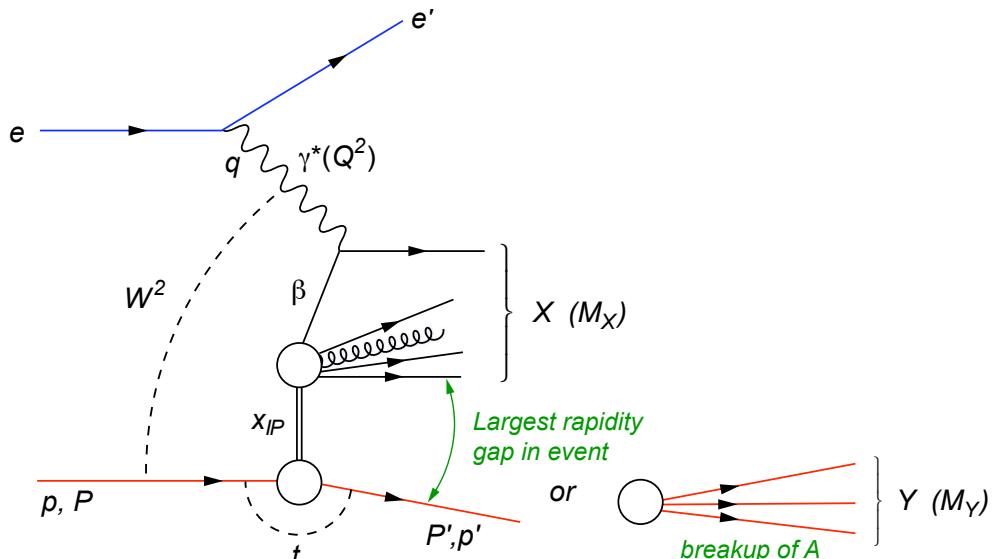
Cyrille Marquet

$$\beta = \frac{Q^2}{2(p-p').(k-k')} = \frac{Q^2}{M_X^2 - t + Q^2}$$

is the momentum fraction of the struck parton w.r.t. the Pomeron

$$x_{IP} = x/\beta$$

momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron



The measured cross-section:

$$\frac{d^4\sigma^{eh \rightarrow eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{em}^2}{\beta^2 Q^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2^{D,4}(x, Q^2, \beta, t) - \frac{y^2}{2} F_L^{D,4}(x, Q^2, \beta, t) \right]$$

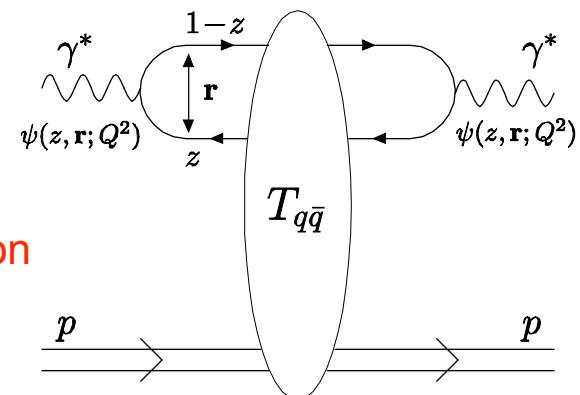
The dipole picture:

Here inclusive DIS

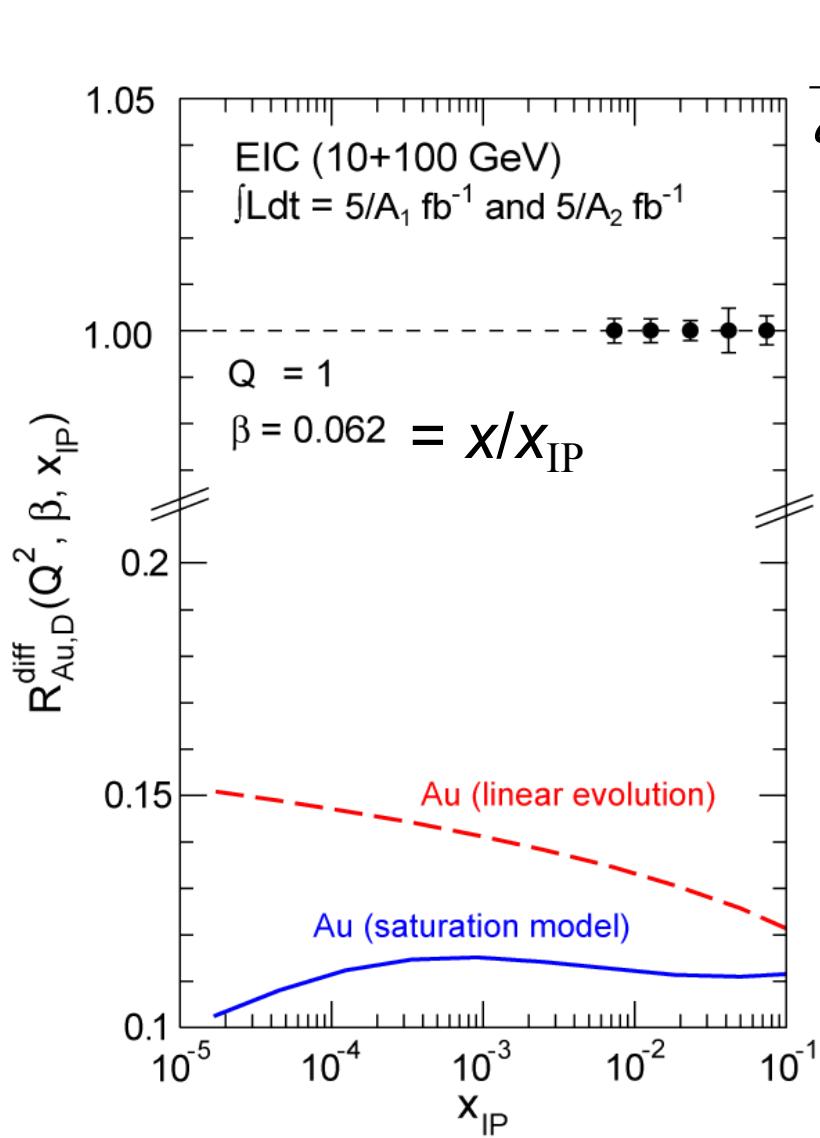
$$\sigma_{tot}^{\gamma^* p \rightarrow X} = 2 \int d^2r dz \sum_{\lambda} |\psi_{\lambda}(r, z, Q^2)|^2 \underbrace{\int d^2b T_{q\bar{q}}(r, x, b)}_{\text{dipole-hadron cross-section}}$$

overlap of  $\gamma^* \rightarrow q\bar{q}$   
splitting functions

dipole-hadron cross-section  
 $T_{q\bar{q}}$  = dipole scattering amplitude



# Diffractive Structure Function $F_2^D$ at EIC



$$\frac{d^4\sigma^{eh \rightarrow eXh}}{dx dQ^2 d\beta dt} = \frac{4\pi\alpha_{e.m.}^2}{\beta^2 Q^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2^D - \frac{y^2}{2} F_L^D \right]$$

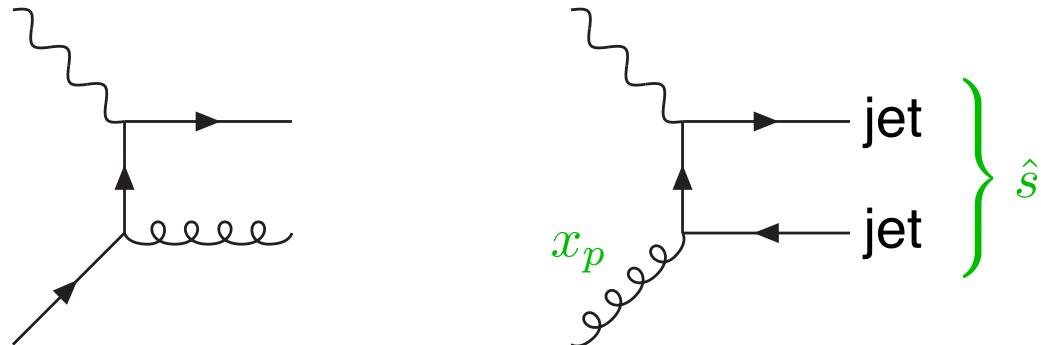
$x_{IP}$  = momentum fraction of the pomeron w.r.t the hadron

- ⇒ Distinguish between linear evolution and saturation models
- ⇒ Insight into the nature of pomeron

# Gluon Distribution from Jet Analysis at EIC

Jets: window to partons, DIS is a clean environment

“2+1 jets” becomes more interesting



Main formula:

$$\frac{d^2\sigma^{2+1}}{dx_p dQ^2} = \alpha_s [a g(x_p, Q^2) + b q(x_p, Q^2)]$$

Technique:

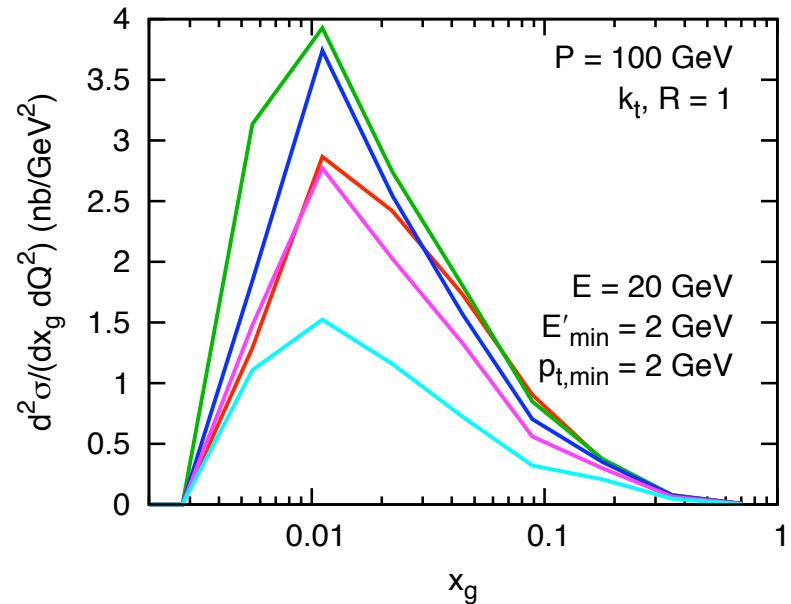
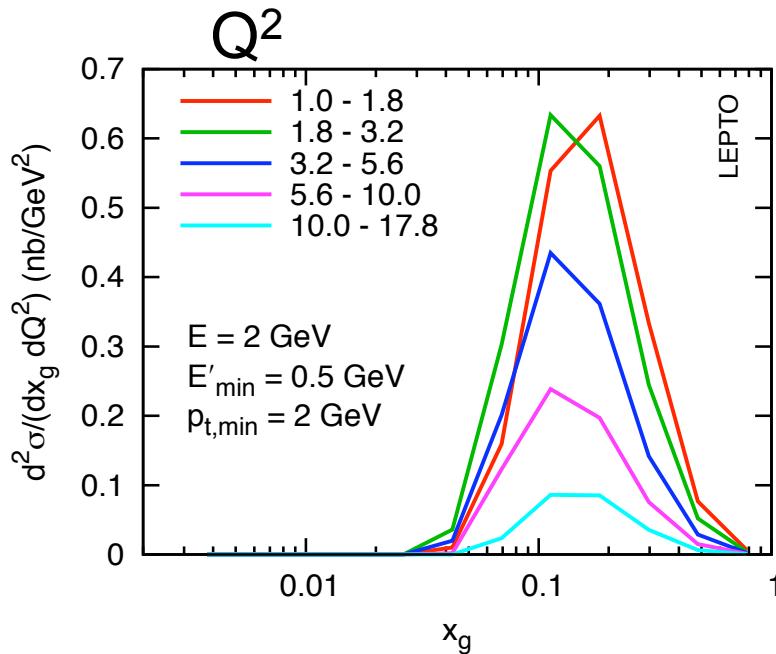
1.  $a$  and  $bq$ : matrix elements & quark piece from Monte Carlo
2.  $x_p = x \left(1 + \frac{\hat{s}}{Q^2}\right)$
3. Extract the gluon distrib:  $g_{\text{extr.}} = \frac{1}{a_{\text{MC}}} (\sigma_{\text{meas.}} - b_{\text{MC}} q)$

# Results from Jets

## Experimental cuts:

- Outgoing electron energy:  $E'_{\min}$
- Minimal jet  $p_T$  :  $p_{T,\min}$
- Azimuthal separation between the 2 jets:  $\Delta\phi > \pi - \varepsilon$  (in the Breit frame — ensures that the 2 jets come from the hard scattering)
- Clustering:  $k_T$  algorithm with  $R=1$  (large but OK in DIS)

Cross-section for gluon-initiated dijet events (obtained with LEPTO)



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Statistical errors assuming 1  $\text{fb}^{-1}$

